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Advancing Optics and Photonics Worldwide

Technical Groups

Nonlinear Frequency Upconversion: A Novel Route for High-Sensitive Mid-Infrared Detection and Imaging

Featuring Dr. Ajanta Barh, Institute for Quantum Electronics, ETH Zurich

5th October 2022

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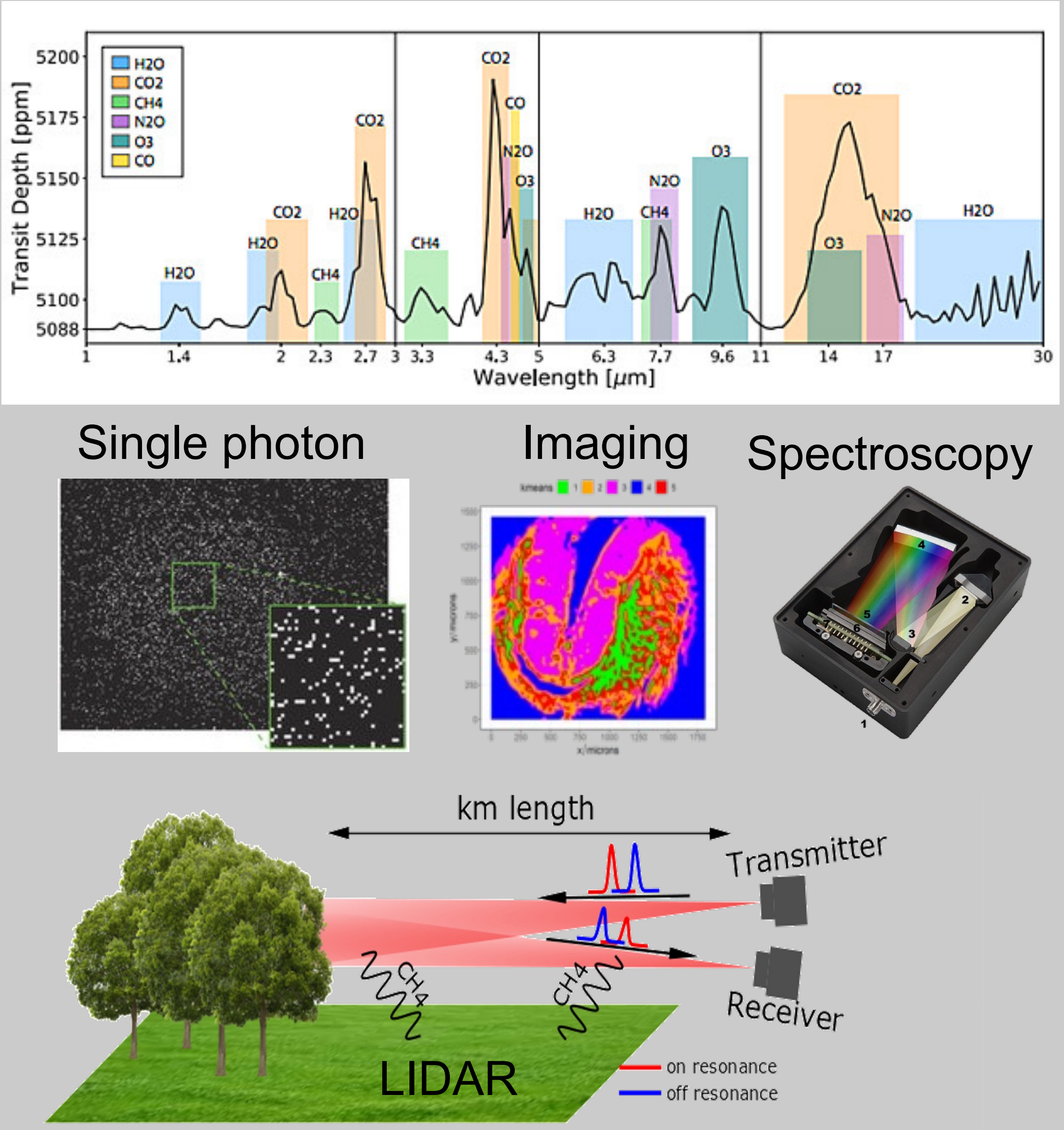
Today's Speaker

Dr. Ajanta Barh

Institute for Quantum Electronics, ETH Zurich

Dr. Ajanta Barh received the Ph.D. degree in Physics from Indian Institute of Technology Delhi, India, in 2015. In 2016, she joined Optical Sensor Technology group at DTU Fotonik, Technical University of Denmark as a postdoc, where she developed novel frequency upconversion based broadband mid-infrared detection and imaging systems. In 2019, she joined the Ultrafast Laser Physics group at ETH Zurich, as a sub-group leader, where she is currently working on ultrafast solid-state and semiconductor laser systems operating in the mid-infrared, towards application in frequency metrology and sensing. Dr. Barh has authored/co-authored more than 60 peer-reviewed journal and conference publications. Her research interests include mid-infrared photonics, nonlinear optics, ultrafast lasers and application. She is currently a senior member of OPTICA and chaired OPTICA Nonlinear Optics Technical group in 2018 - 2020.



NONLINEAR FREQUENCY UPCONVERSION

A novel route for high-sensitive mid-infrared detection and imaging

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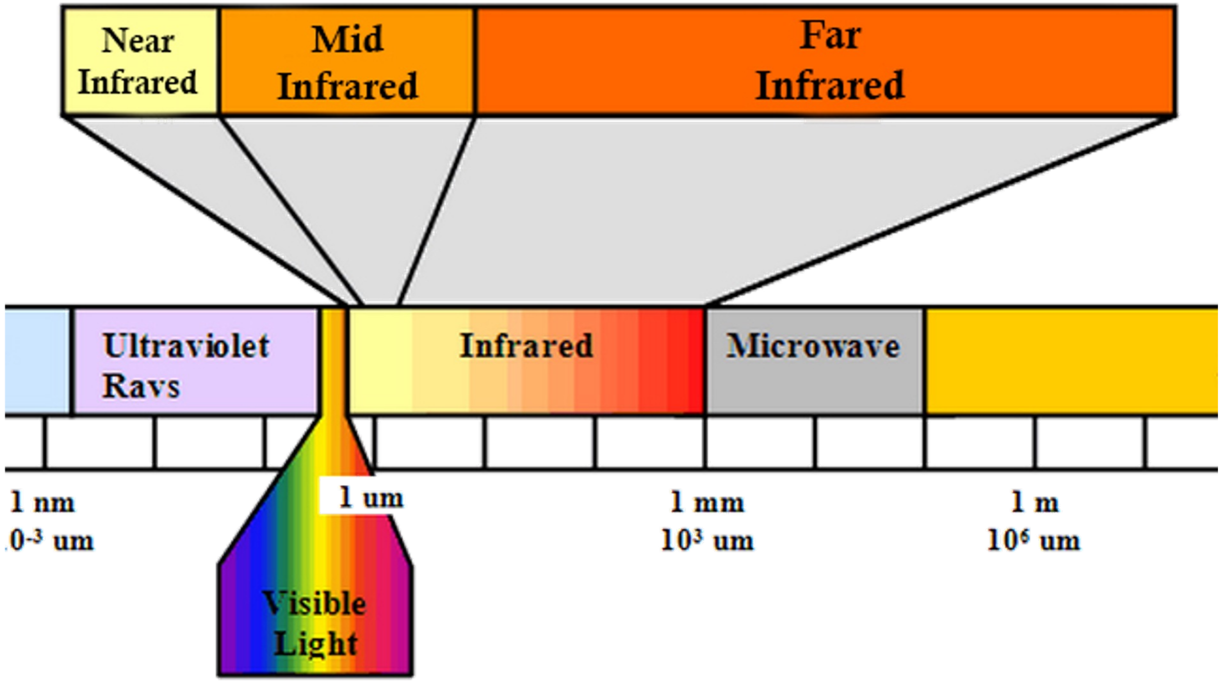
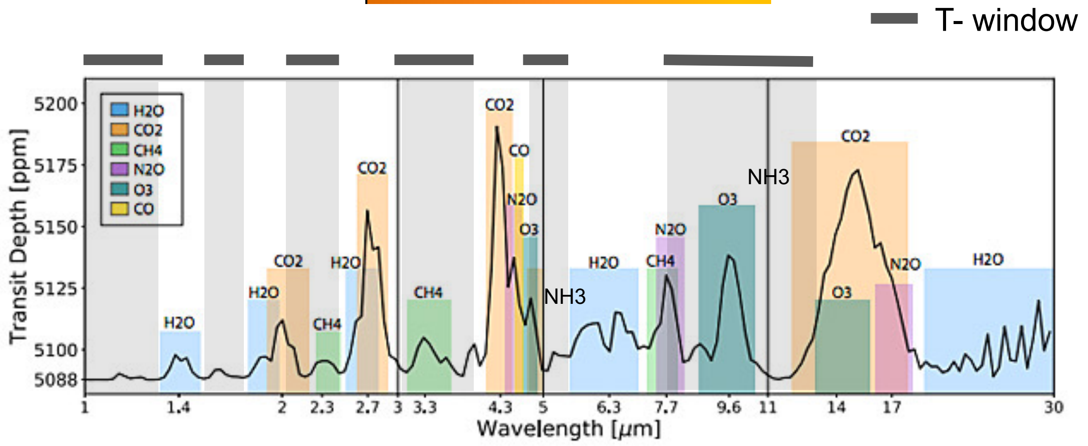
Mid-infrared spectral range

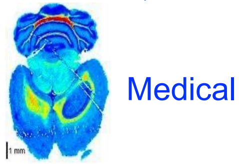
3 – 50 µm



[ISO 20473 scheme]

Mid-infrared (MIR)





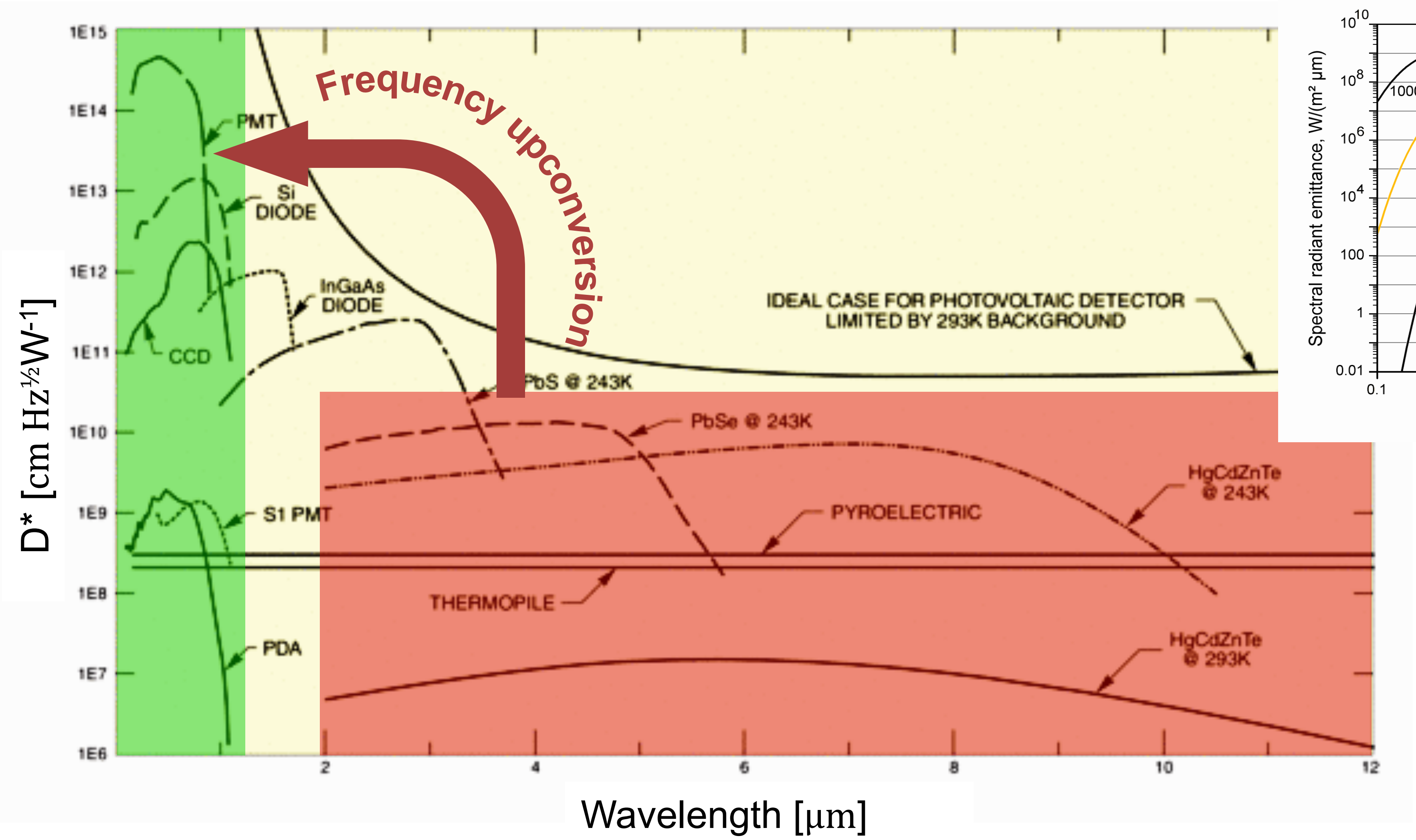
- Fundamental molecular absorption
- Ground-based, long-distance applications
- Thermal detection/imaging

Need: Source, optical components, detector

Topics of discussion

- Challenges in mid-infrared (MIR) detection
- State-of-the-art MIR detectors
- Parametric frequency upconversion: A novel approach
  - ✓ Brief history
  - ✓ Basic theory
  - ✓ Parameters (Bandwidth, efficiency, noise & speed)
  - ✓ Point detection and imaging properties
- Current progress and application examples

MIR detectors



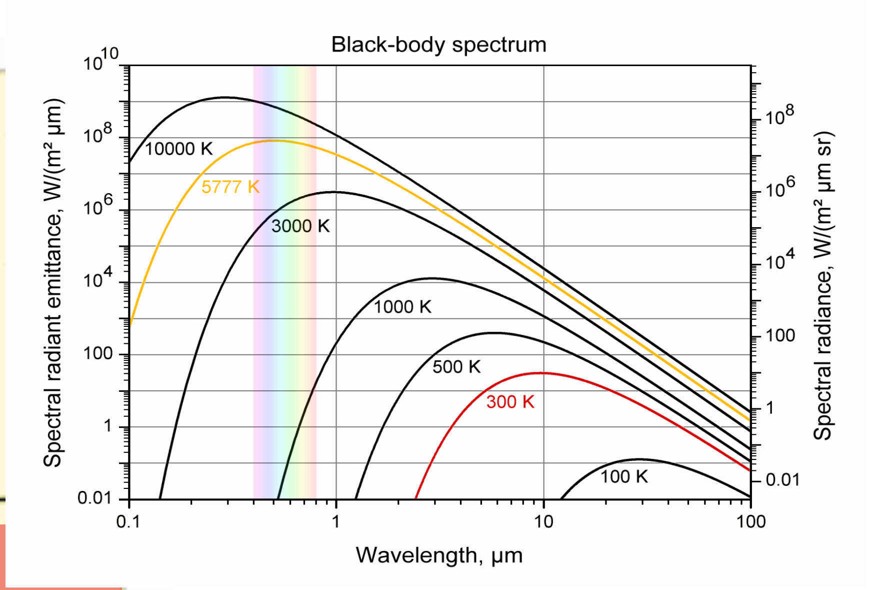
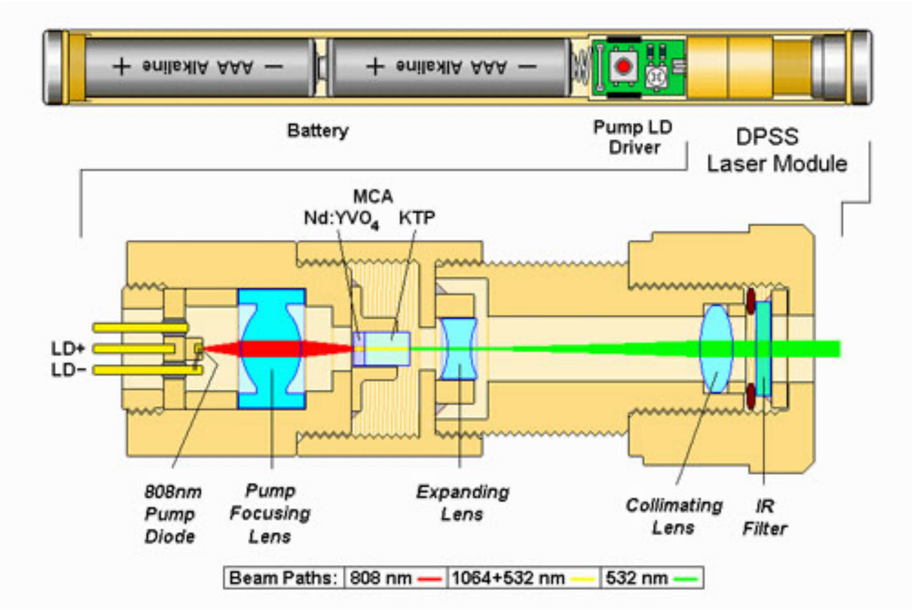
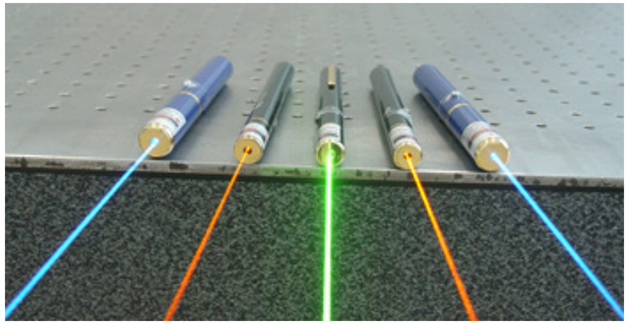


Image from www.Newport.com

Frequency conversion in $\chi^{(2)}$ medium

$$\vec{P} = \varepsilon_0 \chi^{(1)} \vec{E} + \varepsilon_0 \chi^{(2)} \vec{E}^2 + \varepsilon_0 \chi^{(3)} \vec{E}^3 + \ldots$$





$$\frac{1}{1064\text{nm}} + \frac{1}{1064\text{nm}} = \frac{1}{532\text{nm}}$$

$$\frac{1}{946\text{nm}} + \frac{1}{946\text{nm}} = \frac{1}{473\text{nm}}$$

$$\frac{1}{1064\text{nm}} + \frac{1}{1342\text{nm}} = \frac{1}{593\text{nm}}$$

1967

JOURNAL OF APPLIED PHYSICS VOLUME 38, NUMBER 2 FEBRUARY 1967

Up-Conversion of Near Infrared to Visible Radiation in Lithium-meta-Niobate*

J. E. Midwinter and J. Warner
Royal Radar Establishment, Malvern, Worcestershire, England

(Received 18 July 1966; in final form 22 August 1966)

Single-crystal lithium niobate pumped with pulsed ruby-laser radiation has been used to convert 1.7-μ radiation to green light with more than 1% efficiency. A narrow infrared bandwidth of 17 Å, set by the phase-matching requirement only, allows the up-converter and photomultiplier to operate in place of a monochromator and infrared detector, and the emission spectrum of a mercury lamp has been thus examined in the region of 1.7 μ. A close agreement between theory and practice has been found in all respects except noise performance. Further studies of this aspect are required.

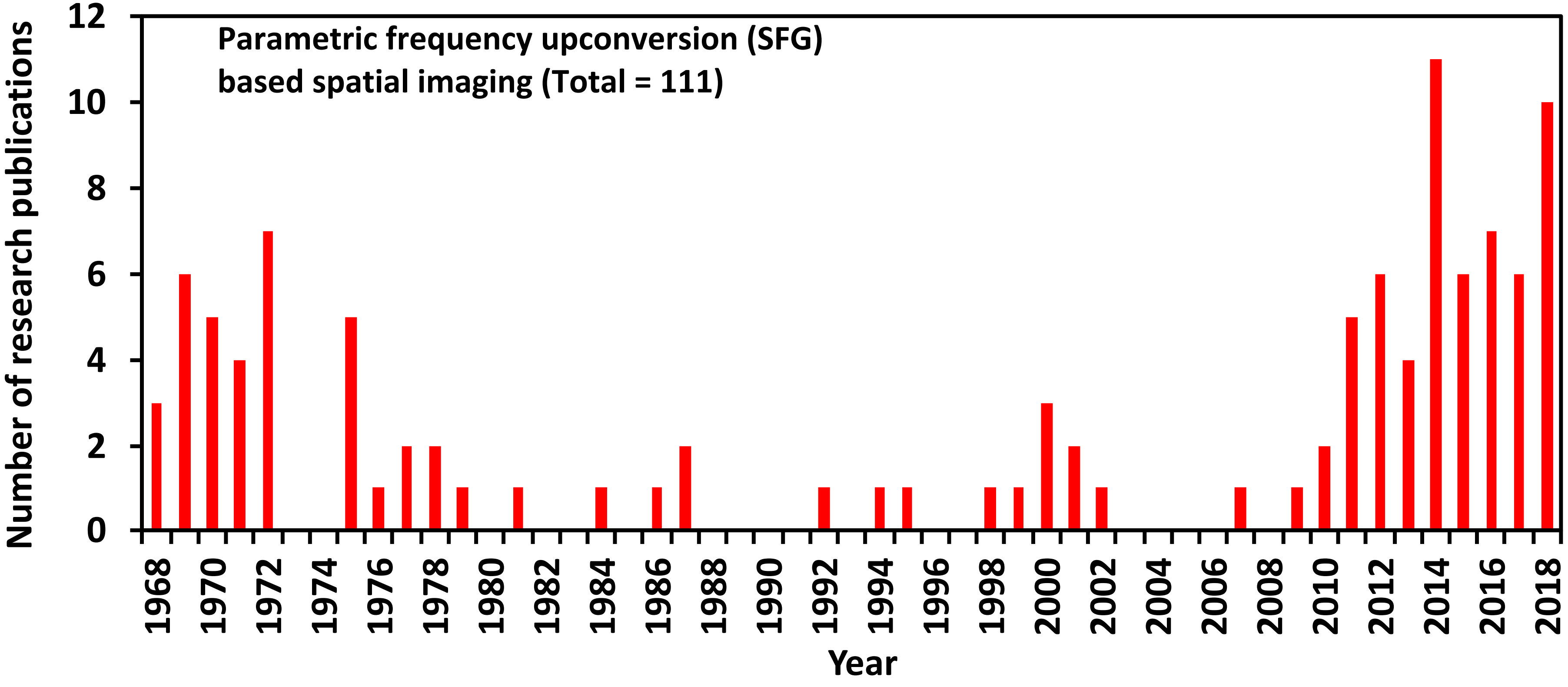
1968

1968 INTERNATIONAL QUANTUM ELECTRONICS CONFERENCE

2B-3 Image Conversion from 1.6 μm to the Visible in Lithium Niobate, J. E. Midwinter,[1] *Royal Radar Establishment, Malvern, Worc., England.*

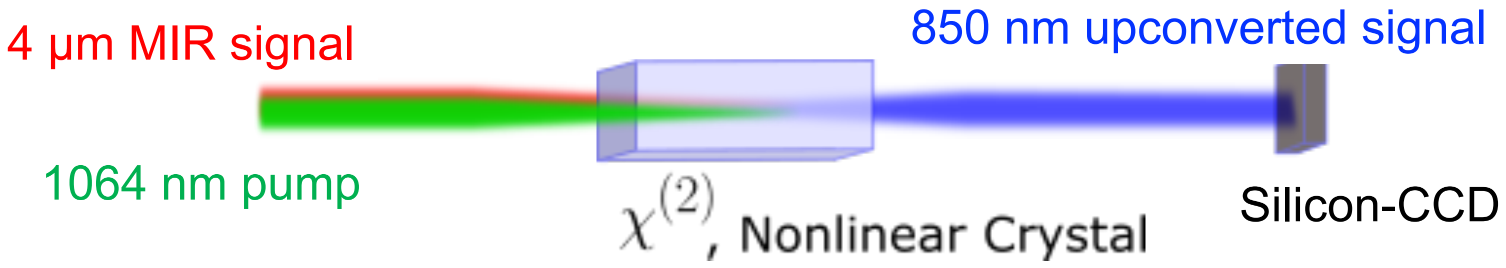
Up-conversion of infrared radiation to the visible in lithium niobate has already been demonstrated by Midwinter *et al.*[2] An extension of that work is reported in which image information carried on a 1.6-μm beam has been converted to the green and photographed in normal manner. This is made possible by the use of a highly collimated laser beam (ruby, 50

Example: Upconversion Imaging

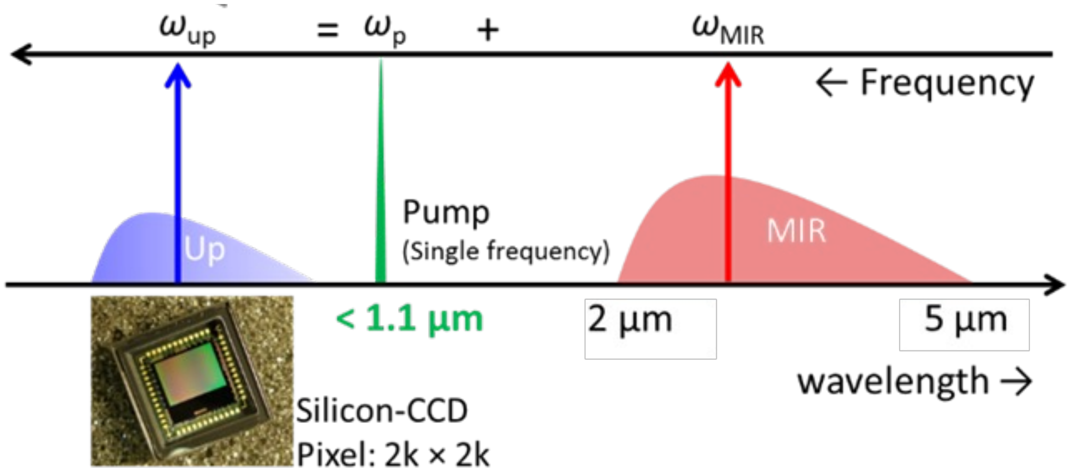


[**Ajanta Barh**, Peter John Rodrigo, Lichun Meng, Christian Pedersen, and Peter Tidemand-Lichtenberg, "Parametric upconversion imaging and its applications," Adv. in Optics & Photonics 11, 952-1019 (**2019**)]

Frequency upconversion based MIR detection



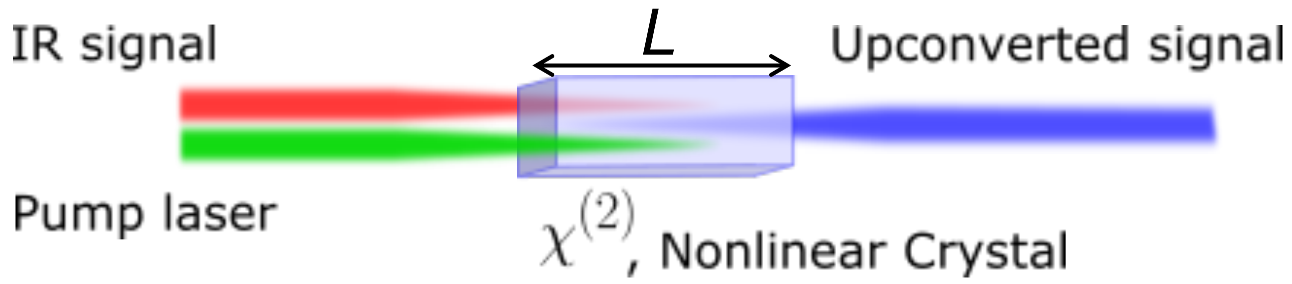
- \+ Conserve spatial/spectral information
- \+ High quantum efficiency
- \+ Linear response
- \+ Low noise
- \+ Fast response time
- \+ Room-temperature operation
- \+ Diffraction limited PSF, large FoV



For detection using Si-CCD, λp < 1.1 µm

PSF: point spread function, FoV: Field of view

Underline principles

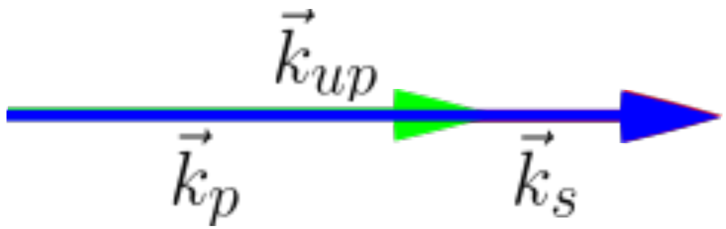


Energy conservation

$$\hbar\omega_p + \hbar\omega_s = \hbar\omega_{up}$$

Momentum conservation

$$\hbar\vec{k}_p + \hbar\vec{k}_s = \hbar\vec{k}_{up}$$



Intensity of MIR signal

Intensity of pump

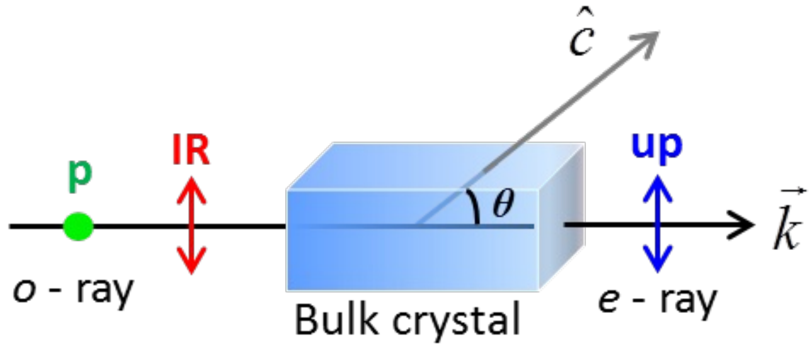
$$I_{up} = \frac{8 d_{eff}^2 \omega_{up}^2 I_s I_p}{n_{up} n_s n_p \varepsilon_0 c^2} L^2 \mathrm{sinc}^2\left(\frac{\Delta k L}{2}\right)$$

2nd order nonlinear coefficient

Phase mismatch

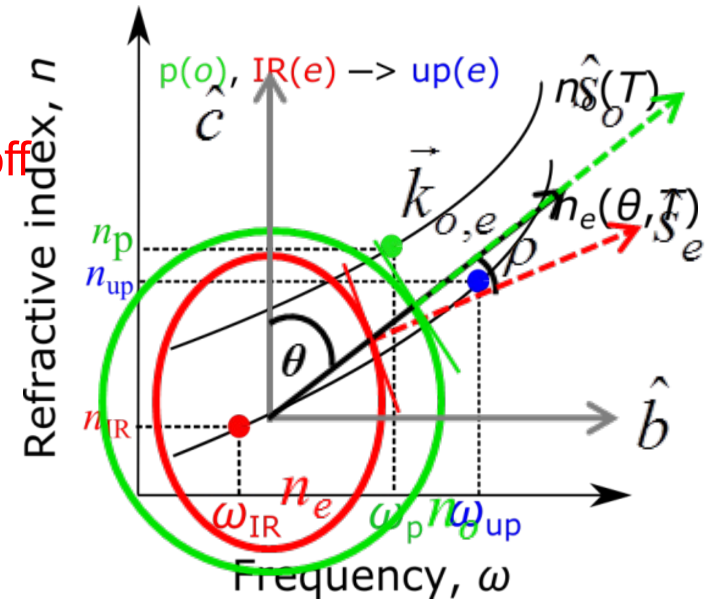
$$\eta_{\text{system}} = \eta_{\text{up}} \times \eta_{\text{det}} \times \eta_{\text{ext-loss}}$$

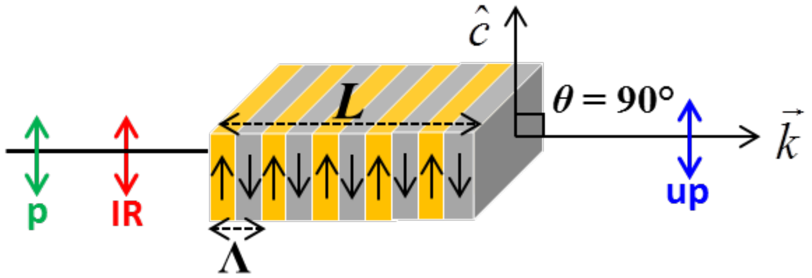
Ways to satisfy phase-matching



$$\Delta\vec{k} = \vec{k}_p + \vec{k}_{IR} - \vec{k}_{up} = \omega_p n_p + \omega_{IR} n_{IR} - \omega_{up} n_{up}$$

Walk-off





Quasi-phase matching (QPM) :

$$\Delta\vec{k} = \vec{k}_p + \vec{k}_s - \vec{k}_{up} - m\frac{2\pi}{\Lambda}\hat{z} = 0$$

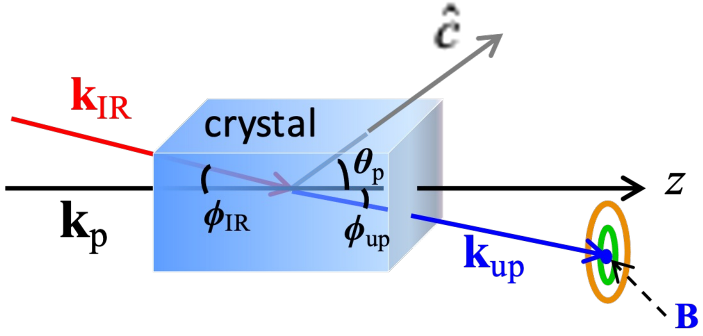
- \+ No spatial walk-off
- \+ Extra design freedom (Λ) -> wavelength tuning
- \+ High d_{eff} (diagonal tensor element)
- \- Introduces extra noise

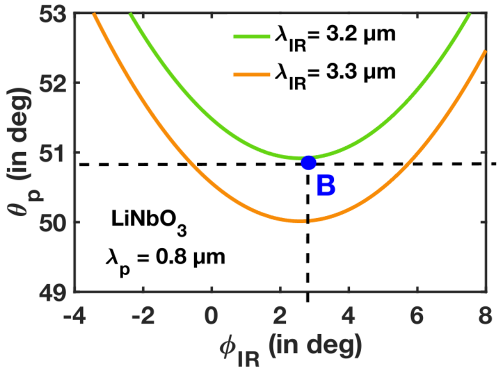
Collinear

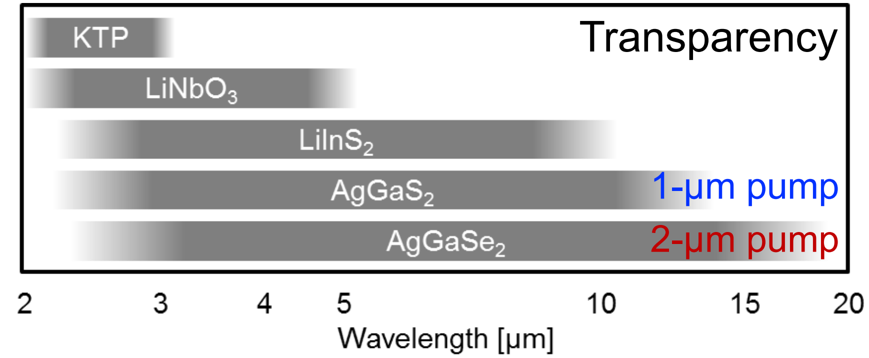
✓ point detection, efficient narrow-band upconversion

Design parameters

Non-collinear

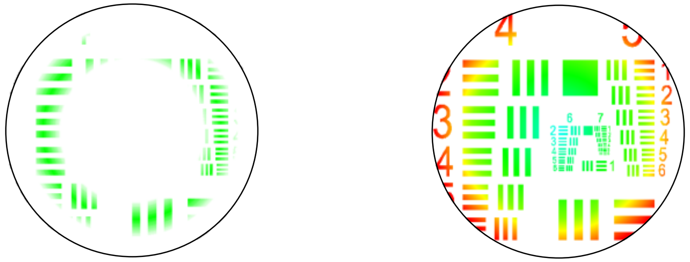


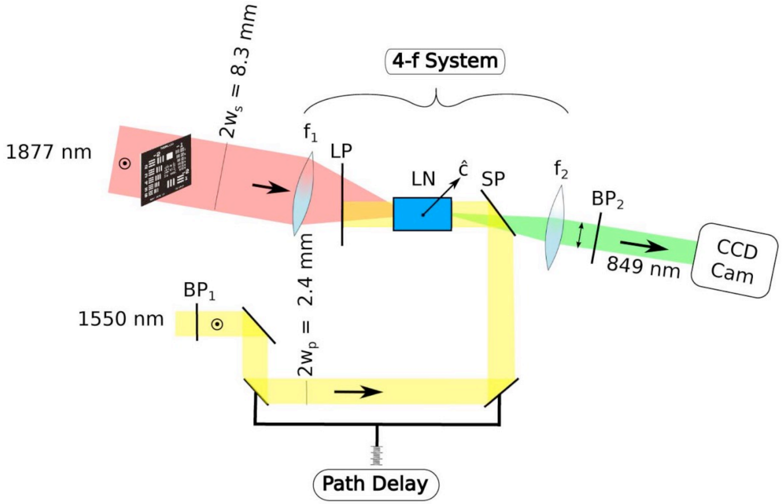




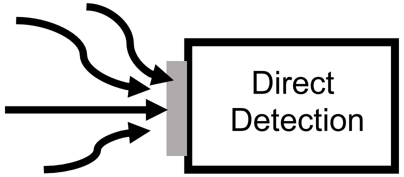
Transparent for all three waves

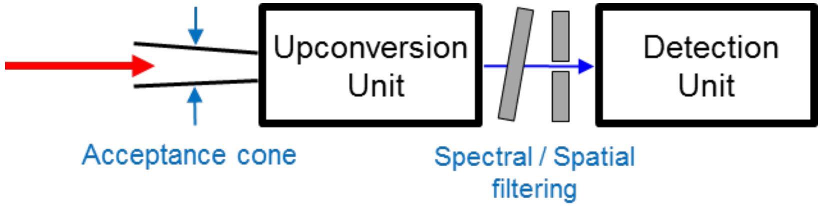
Narrowband / Broadband





Acceptance parameters





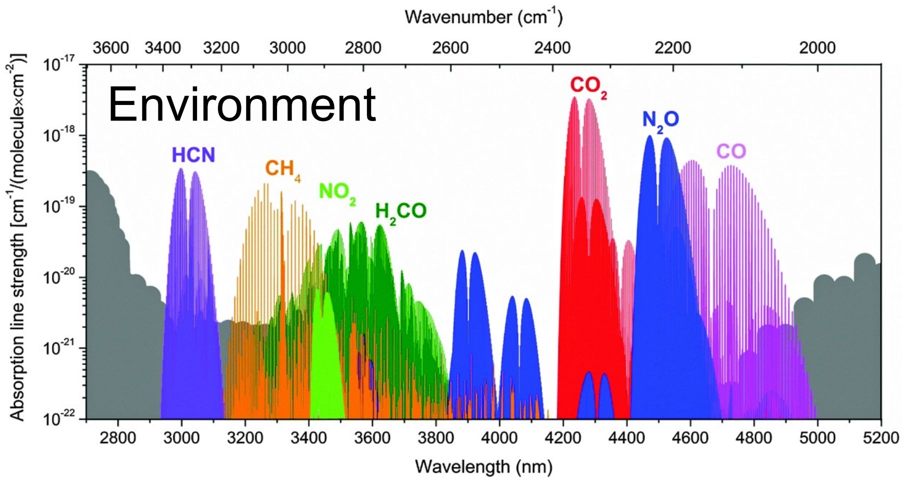
Temporal bandwidth: CW mixing / Synchronized mixing

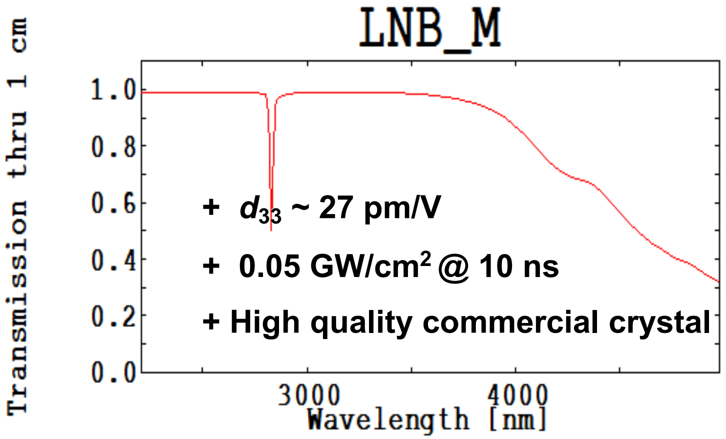
[M. Mathez, P. J. Rodrigo, P. Tidemand-Lichtenberg, and C. Pedersen, “Upconversion imaging using short-wave infrared picosec- ond pulses,” Opt. Lett. 42, 579–582 (2017)]

Case study with $LiNbO_3$

$LiNbO_3$ is the nonlinear material of choice for **2 – 5 µm**

- ✓ Bulk geometry (high power, imaging)
- ✓ Chip-scale, µm – nm scale (high efficiency, single photon)

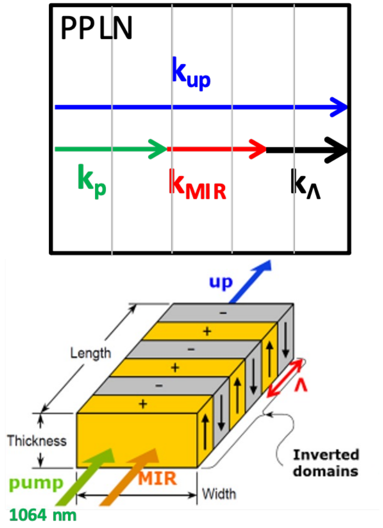


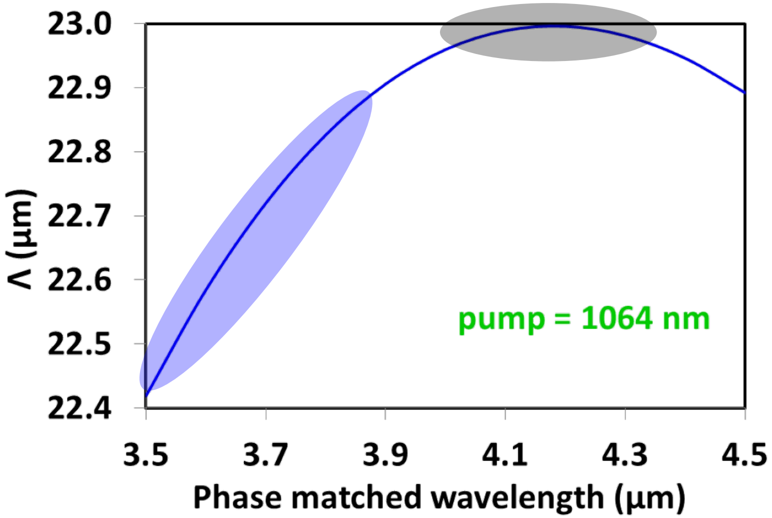


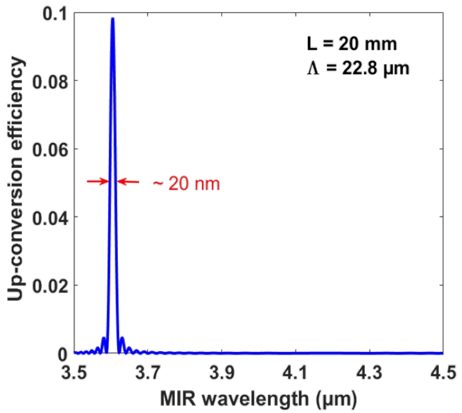
+ d_{33} ~ 27 pm/V
+ 0.05 GW/cm^2 @ 10 ns
+ High quality commercial crystal

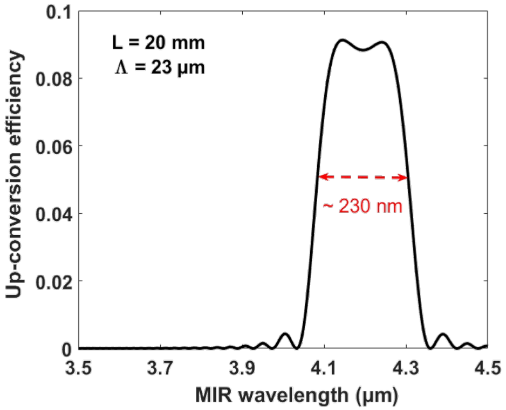
Spectral bandwidth maximization

PPLN: periodically poled lithium niobate









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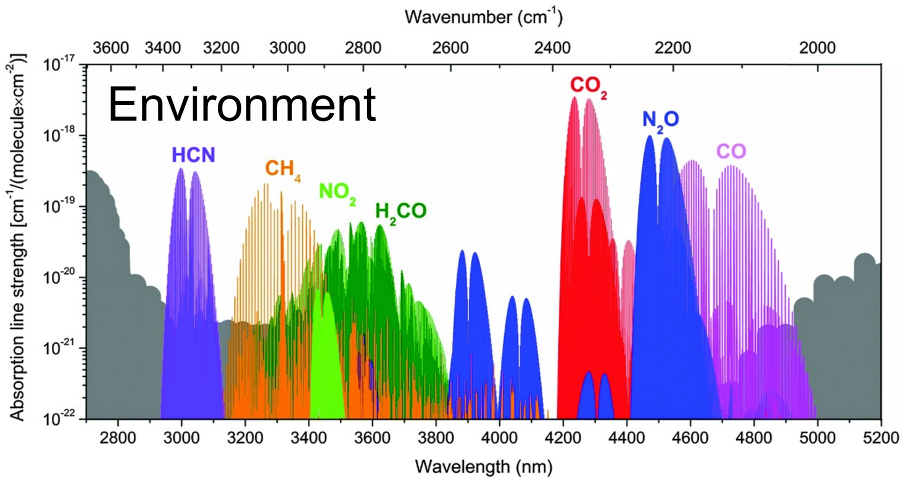

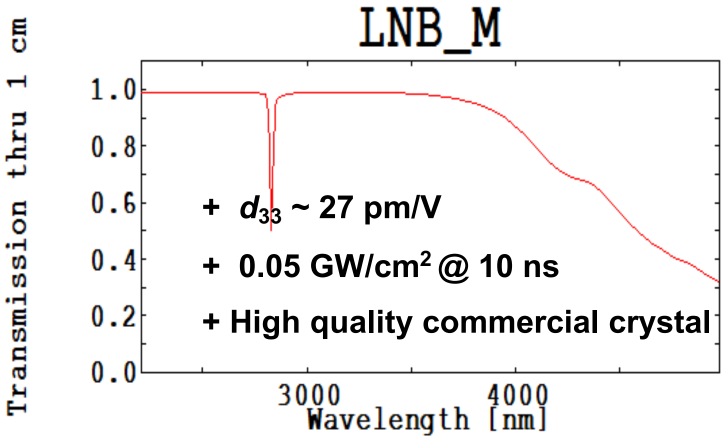

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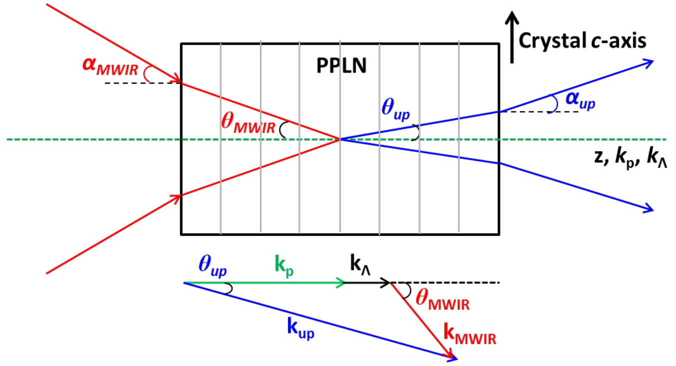
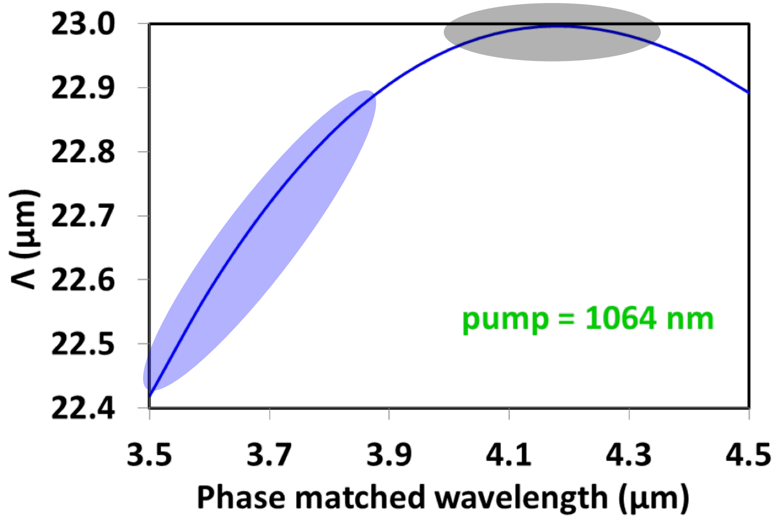
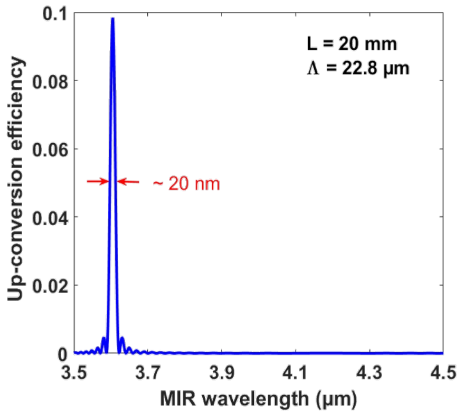
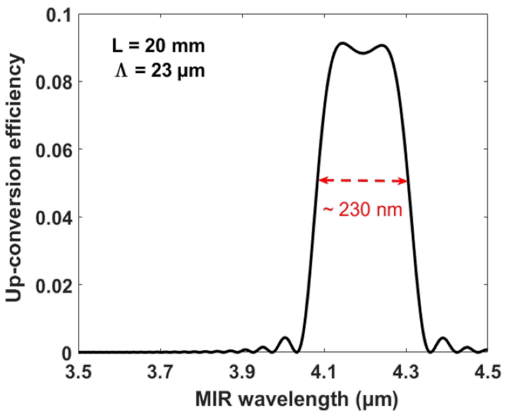
- \+ High quality commercial crystal

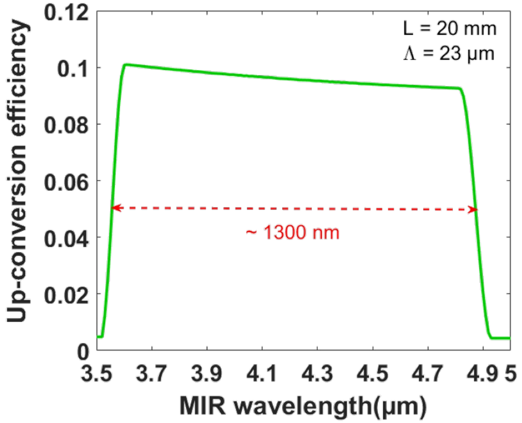
Spectral bandwidth maximization





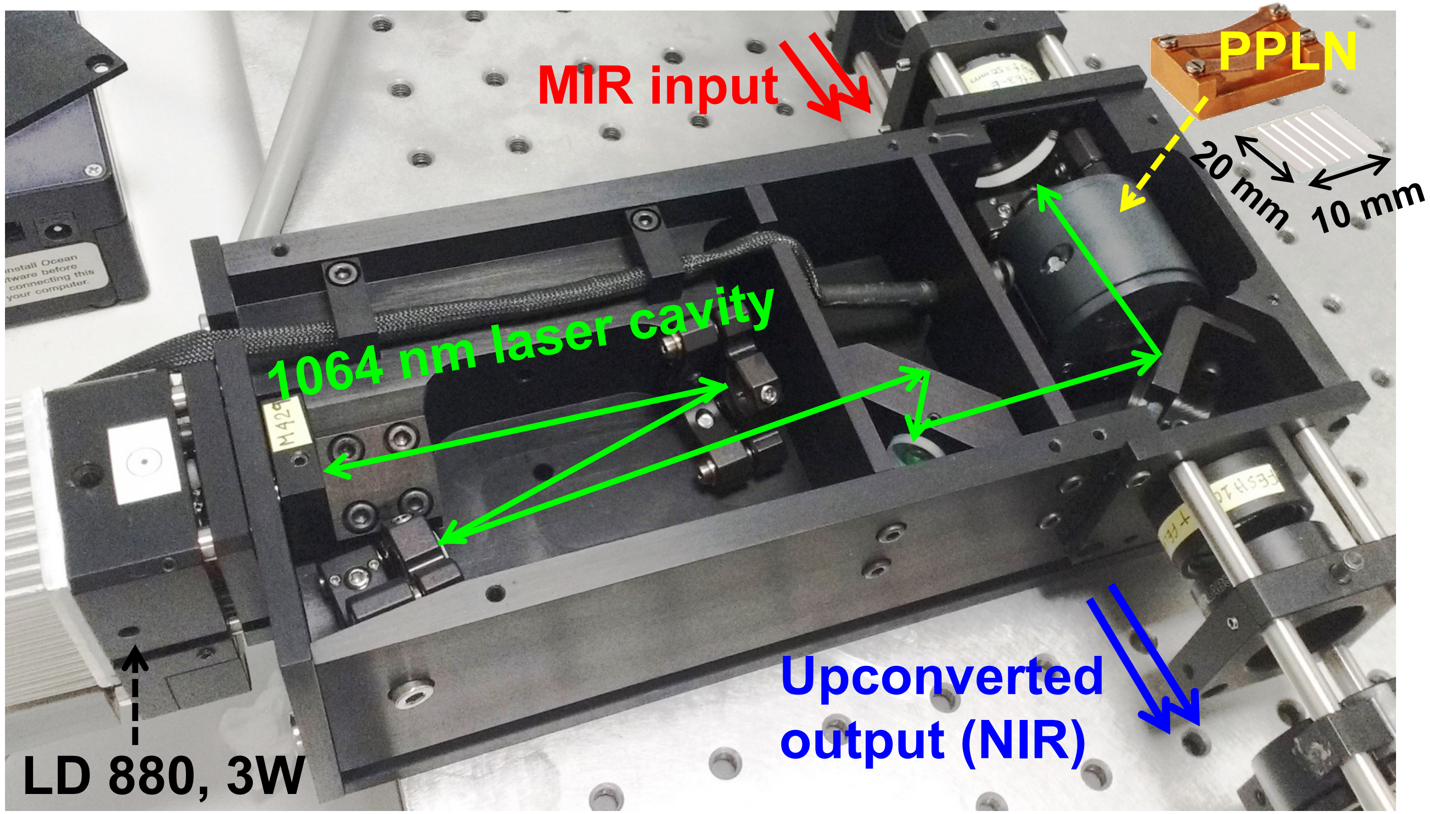




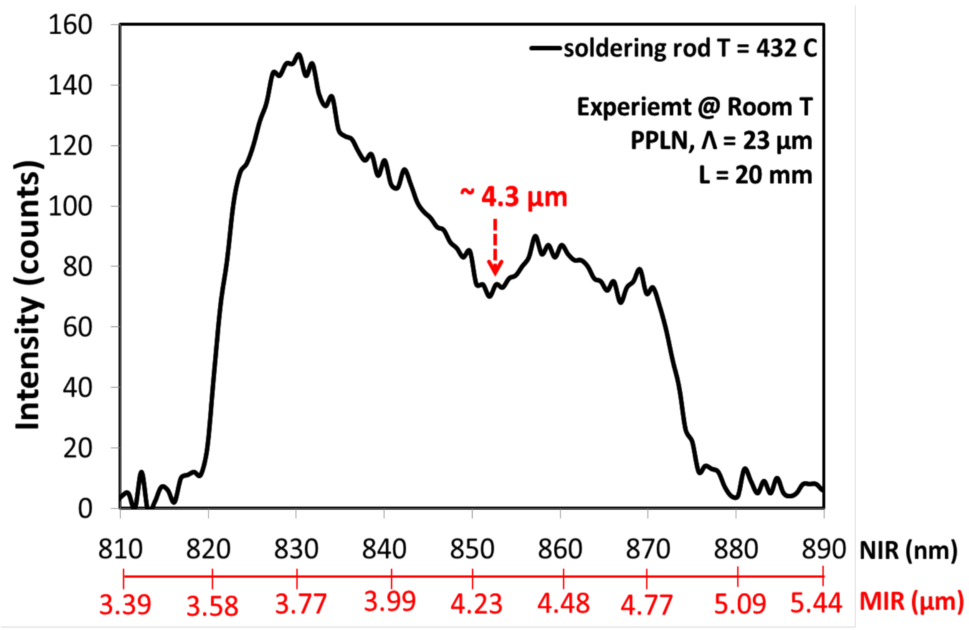


Broadband upconversion using $LiNbO_3$

Size of a **shoe-box**



MIR source: hot soldering rod



Conversion efficiency ~ 1% (over entire bandwidth)

Ultra-broadband mid-wave-IR upconversion detection

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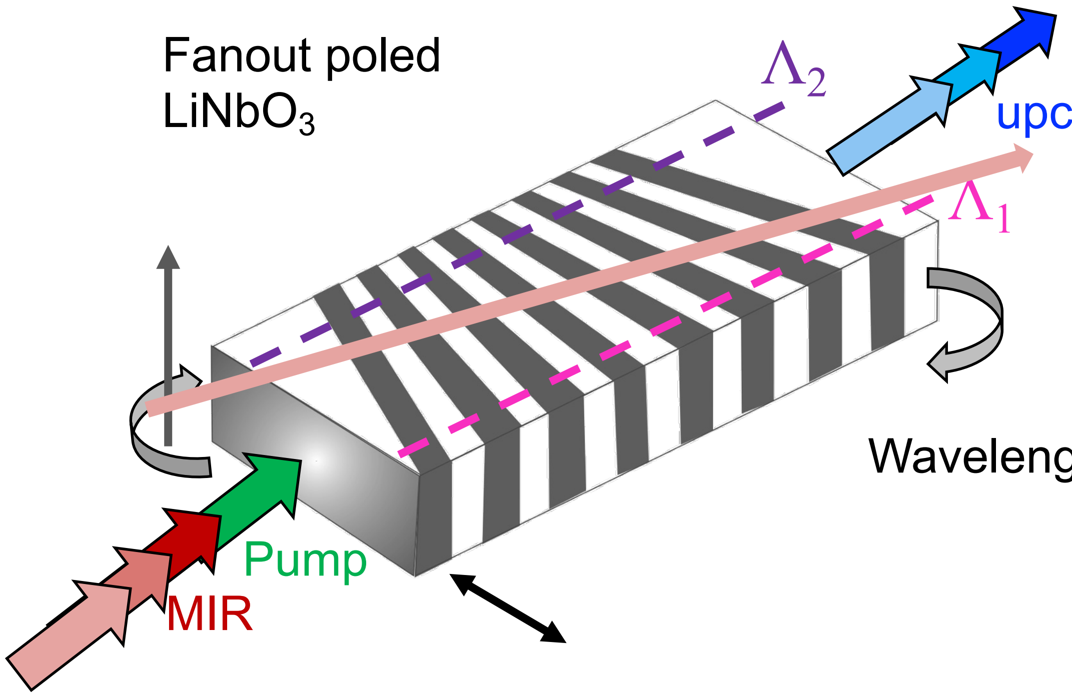
AJANTA BARH,* CHRISTIAN PEDERSEN, AND PETER TIDEMAND-LICHTENBERG

DTU Fotonik, Technical University of Denmark, DK-4000 Roskilde, Denmark
**Corresponding author: ajaba@fotonik.dtu.dk*

Trailoring spectral response using $LiNbO_3$

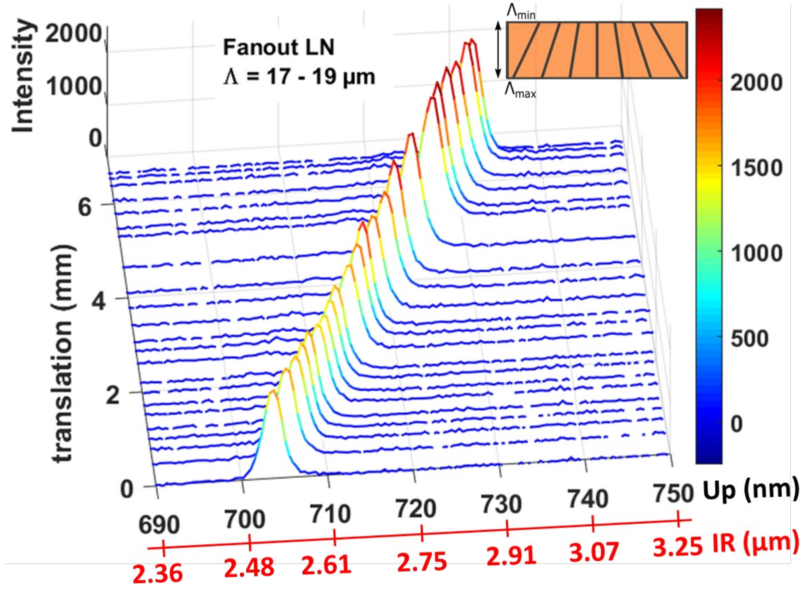


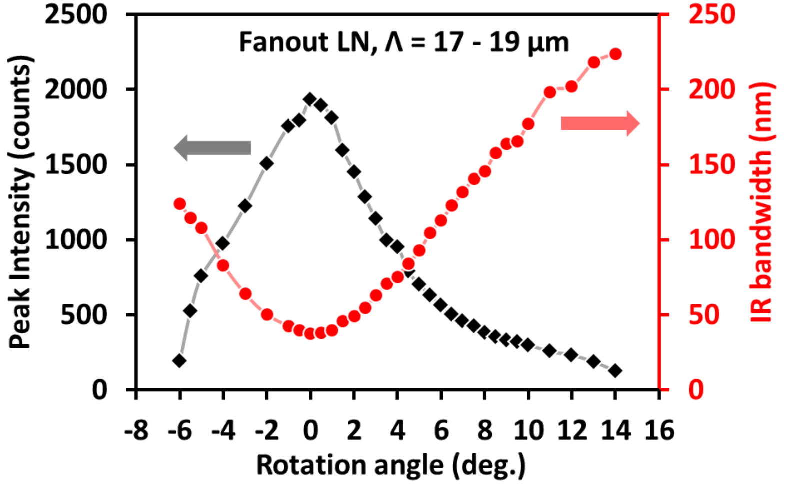
Λ: 17 – 19 μm

Wavelength: 2.5 – 3.0 μm

Collinear

Rotation
- ✓ mimics a chirped structured
- ✓ simultaneous generation of many wavelengths
- ✓ peak efficiency decreases





Upconversion spectral response tailoring using fanout QPM structures Vol. 44, No. 11 / 1 June 2019 / *Optics Letters*

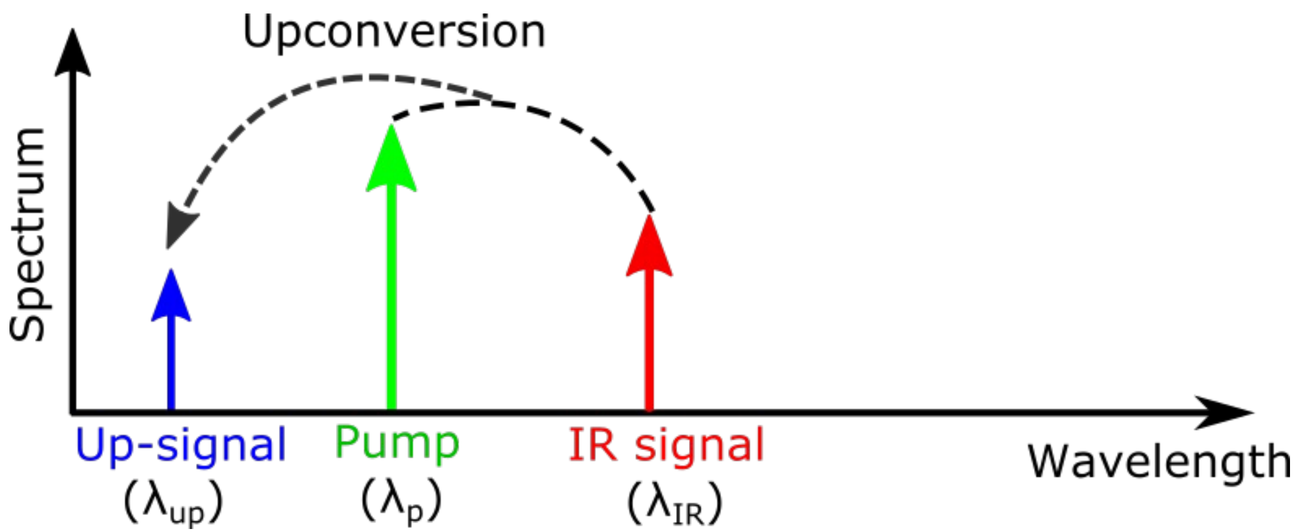
AJANTA BARH,[1,*] MAHMOUD TAWFIEQ,[2] BERND SUMPF,[2] CHRISTIAN PEDERSEN,[1] AND PETER TIDEMAND-LICHTENBERG[1]

Noise

How low signal level it can detect? -> noise/**noise equivalent power (NEP)**?

1. Upconversion process
2. Photodetector

Si-photodiode (PDF10A, thorlabs): ~ $1.5\ fW/\sqrt{Hz}$

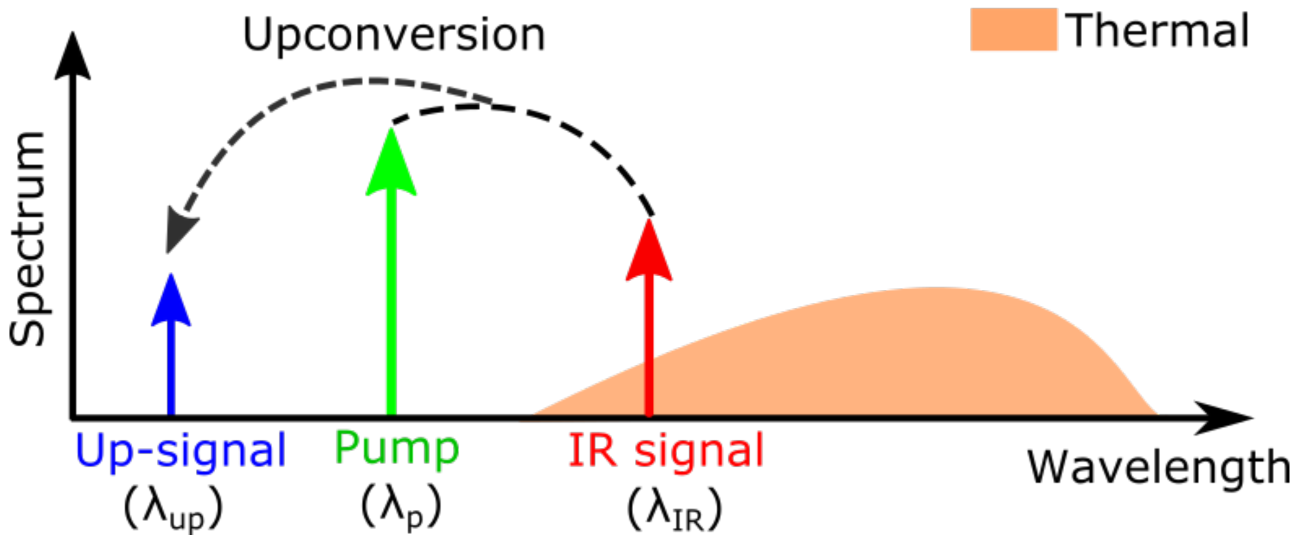


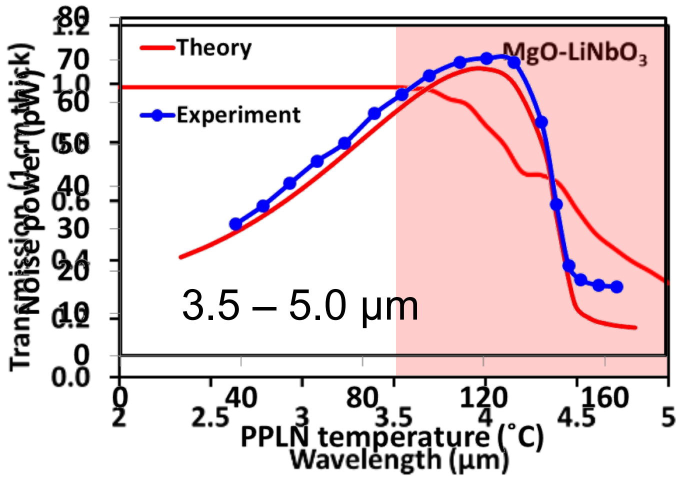
Noise

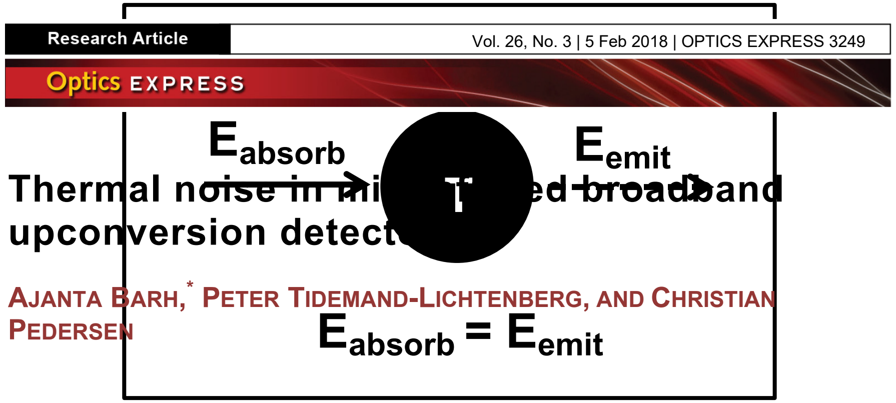
Where an upconversion detector stands in terms of noise/**noise equivalent power (NEP)**?

1. Upconversion process
2. Photodetector

Si-photodiode (PDF10A, thorlabs): ~ $1.5\ fW/\sqrt{Hz}$



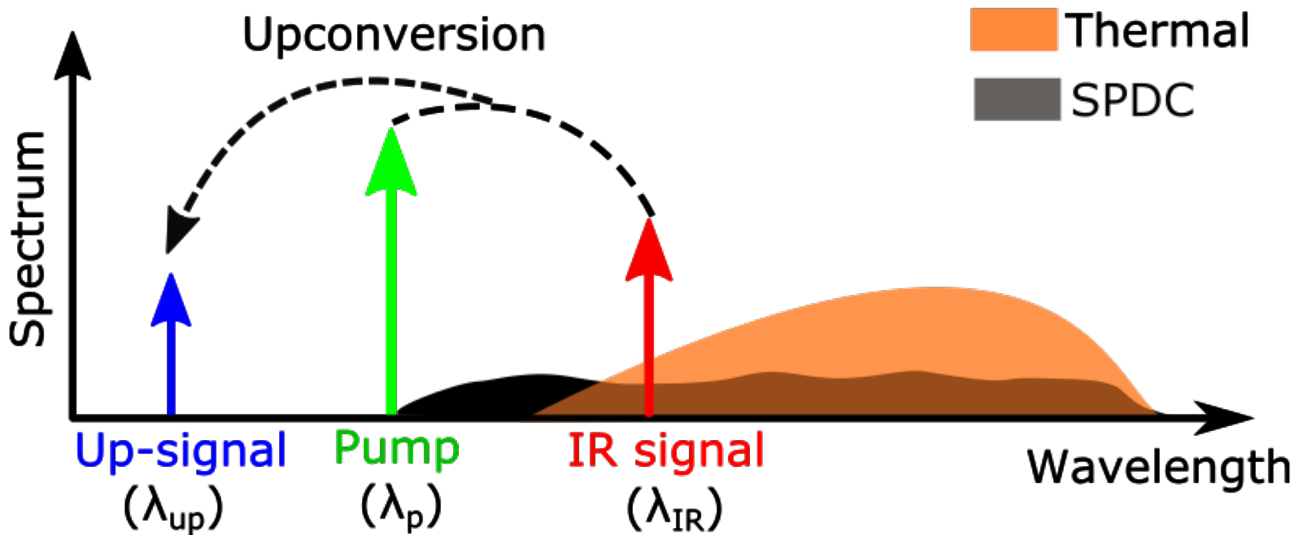


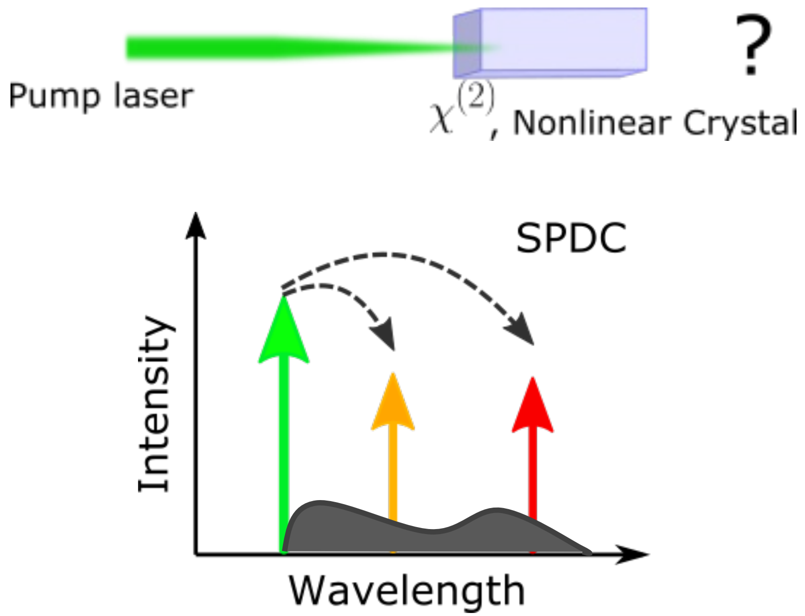


Noise

What are the noise sources? noise equivalent power (**NEP**)?

1. Upconversion process
2. Photodetector Si-photodiode (PDF10A, thorlabs): ~ $1.5\ fW/\sqrt{Hz}$





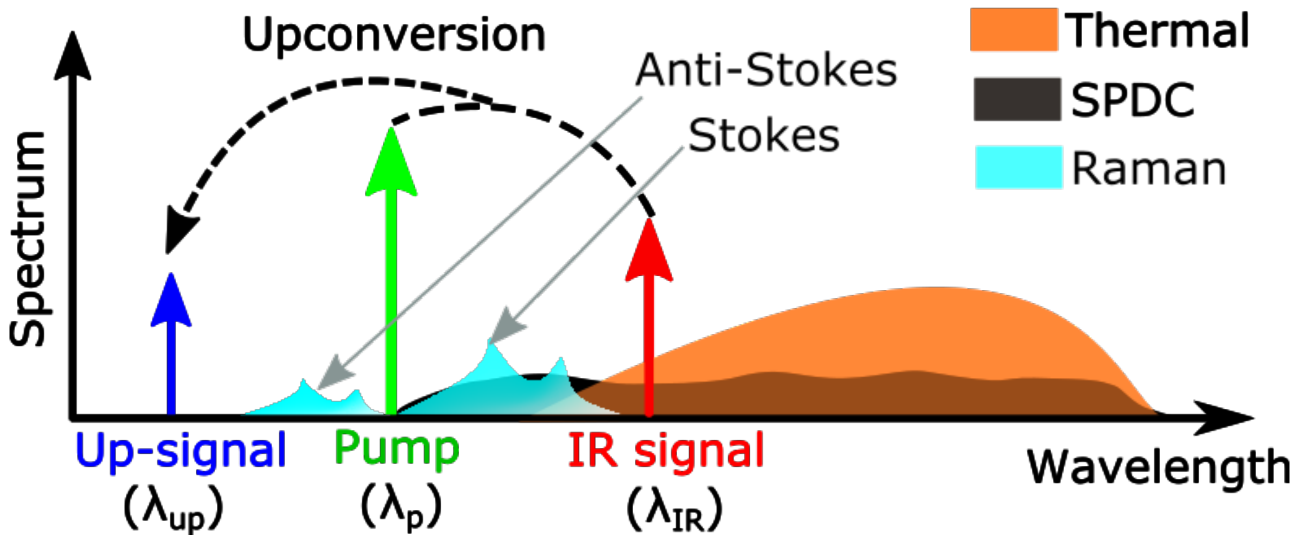
C. R. Phillips, J. S. Pelc, and M. M. Fejer, J. Opt. Soc. Am. B 30, 982–993 (2013).

L. Meng, L. Høgstedt, P. Tidemand-Lichtenberg, C. Pedersen, and P. J. Rodrigo, Opt. Exp. 26, 24712–24722 (2018).

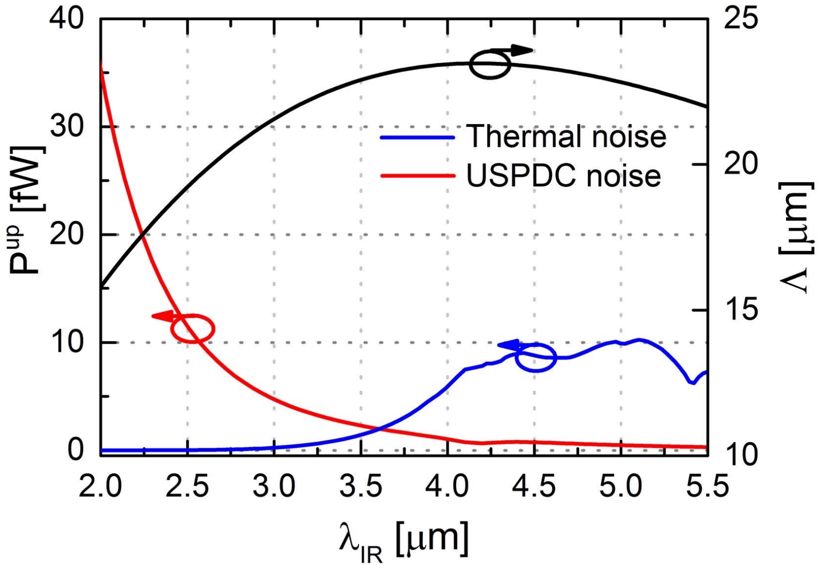
Noise

Where an upconversion detector stands in terms of noise/**noise equivalent power (NEP)**?

1. Upconversion process
2. Photodetector   Si-photodiode (PDF10A, thorlabs): ~ $1.5\ fW/\sqrt{Hz}$



PPLN upconversion detector



- Collinear
- Spectral filter (narrow band)

R. L. Pedersen, L. Høgstedt, **A. Barh**, L. Meng, and P. Tidemand-Lichtenberg, IEEE Photon. Technol. Lett. 31, 681–684 (2019)

P. S. Kuo, J. S. Pelc, C. Langrock, and M. M. Fejer, Opt. Lett. 43, 2034–2037 (2018).

Noise comparison

NEP COMPARISON OF DETECTORS

Detector	Bandwidth [Hz]	NEP* [pW/$\sqrt{\text{Hz}}$]	NEP upc.** [pW/$\sqrt{\text{Hz}}$]	η_{up}	η_{total}
PDF10A+UpC	20	$1.4 \cdot 10^{-3}$	$2.0 \cdot 10^{-2}$	6.0%	2.0 %
Vigo PVI-4TE-5-1x1	$55 \cdot 10^{6}$	1.0	NA	NA	66%
Teledyne 0.1 mm	$50 \cdot 10^{6}$	$80 \cdot 10^{-3}$	NA	NA	55%
Hamamatsu+UpC***	$1 \cdot 10^{9}$	$1.5 \cdot 10^{-3}$	75	$3.6 \cdot 10^{-6}$	$2.7 \cdot 10^{-6}$
Perkin-Elmer+UpC***	$7 \cdot 10^{9}$	$0.86 \cdot 10^{-3}$	43	$3.6 \cdot 10^{-6}$	$2.7 \cdot 10^{-6}$
SPC+UpC****	NA	$1.3 \cdot 10^{-5}$	$2.6 \cdot 10^{-5}$	32.9%	10.5%

* The NEP of the photodetector.
** The NEP for upconversion detector (photodetector + upconversion module).
*** The results are reproduced from [16].
**** The results are reproduced from [17], SPC stands for single photon counter. A pulsed laser is used as the pump in [17], NEP upc., η_{up} and η_{total} are the instantaneous values when the pump is at the peak power.

Upconversion detection integration time ~ μs – ms range

IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 31, NO. 9, MAY 1, 2019 681

Characterization of the NEP of Mid-Infrared Upconversion Detectors 2019

Rasmus Lyngbye Pedersen, Lasse Høgstedt, Ajanta Barh, Lichun Meng, and Peter Tidemand-Lichtenberg

Low noise
- Low signal/single photon
- LIDAR (low backscattered signal)

Longer wavelength upconversion

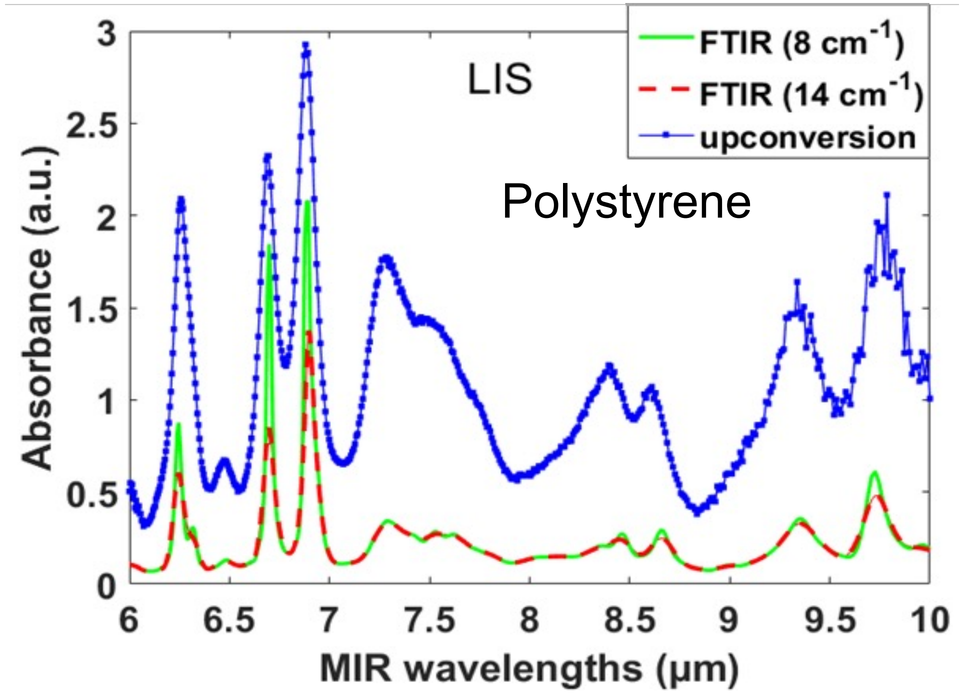
Limited choice of material for pumping at 1 µm

Mid-Infrared (6 - 10 µm) upconversion in $LiInS_2$ using 1064 nm CW pump

A. Barh, L. Høgstedt, P. Tidemand-Lichtenberg, and C. Pedersen

CLEO: Science and Innovations 2018
San Jose, California United States
13–18 May 2018
ISBN: 978-1-943580-42-2

From the session
Optical Metrology Nonlinear Optical Technologies (SM4D)



ORIGINAL PAPER
LASER & PHOTONICS REVIEWS
www.lpr-journal.org

$AgGaS_2$

Room-Temperature, High-SNR Upconversion Spectrometer in the 6–12 µm Region

2022

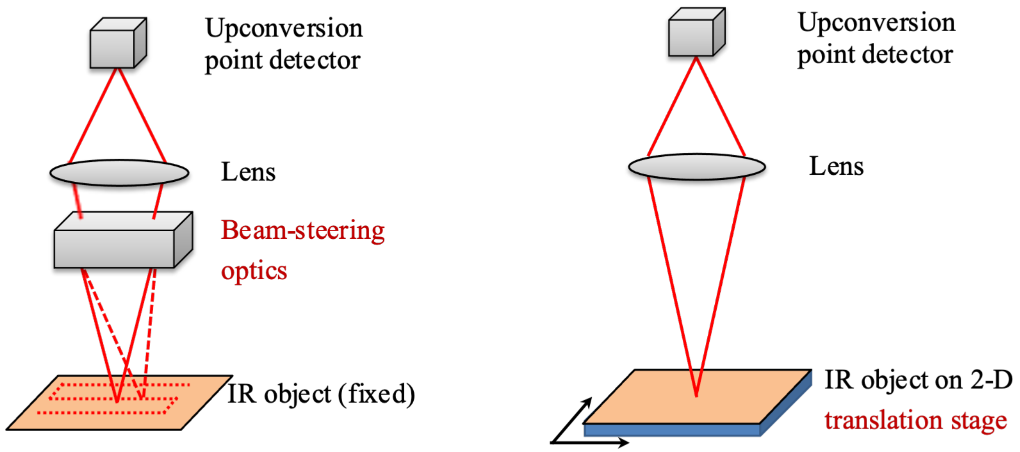
Peter John Rodrigo, Lasse Høgstedt, Søren Michael Mørk Friis, Lars René Lindvold, Peter Tidemand-Lichtenberg, and Christian Pedersen*

Table 1. Comparison of MIRUS and the two types of FTIR—three spectrometers used in the MIR fingerprint region using globar illumination.

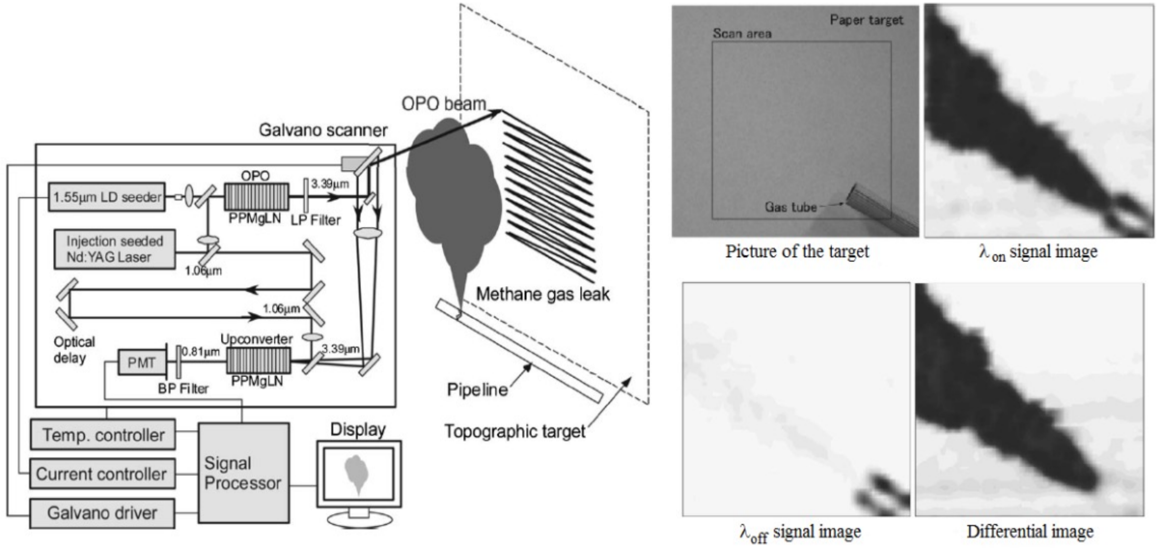
Parameter	MIRUS	FTIR (temporal)	FTIR (spatial)
Detector type	Si	HgCdTe	HgCdTe
Requires detector cooling?	No	Yes[a)]	Yes[b)]
Requires moving parts?	No	Yes	No
Spectral range [cm^{-1}]	830–1750	350–7800	800–4000
Spectral resolution [cm^{-1}]	6[c)]	0.09, 2, 4, 8, 16	4
Measurement rate [spectra s^{-1}]	40[d)]	22.5[e)] at 4 cm^{-1}	0.5
SNR at 1 s	>10 000	≈6000[e)] at 4 cm^{-1}	1400

Point detection vs imaging

Straightforward way from **point detection -> imaging**: Raster scanning technique



- Resolution: Spot size
- FoV: scanning range

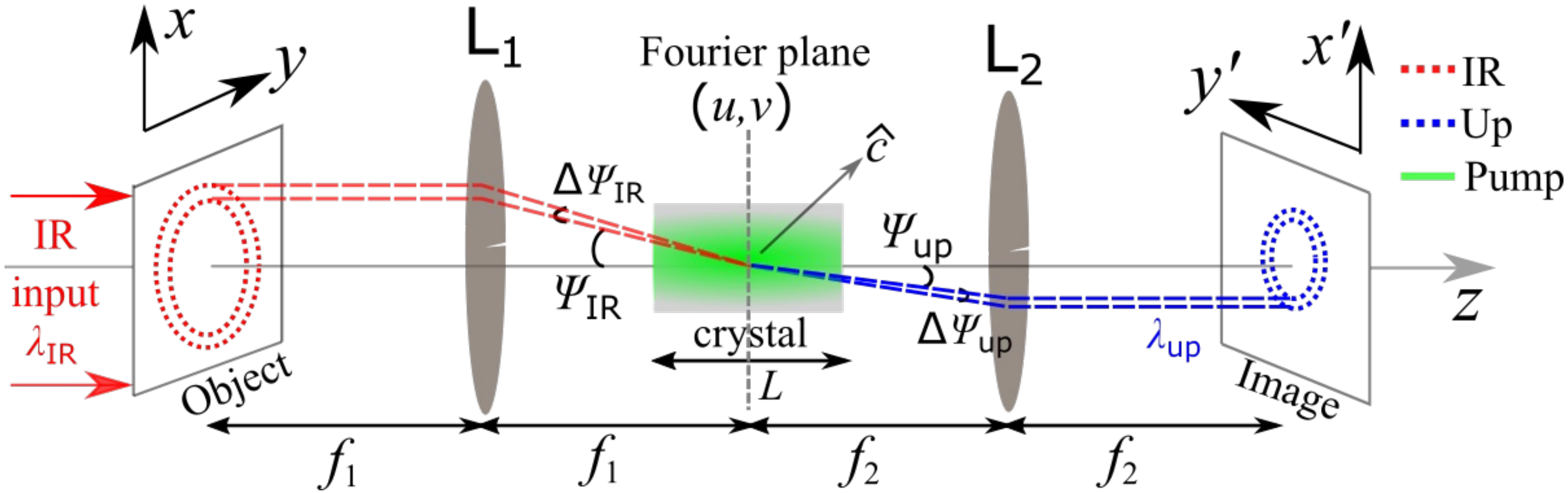


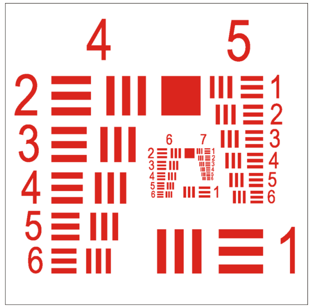
Imaging at 3.39 µm gas leaks of CH_4 from a pipe using on/off-resonance wavelengths

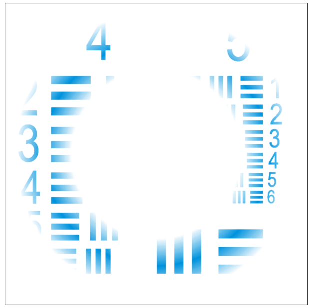
[M. Imaki and T. Kobayashi, "Infrared frequency upconverter for high-sensitivity imaging of gas plumes," *Opt. Lett.*, vol. 32, no. 13, pp. 1923–1925, Jul. 2007]

Full field of view (FoV) imaging

Monochromatic illumination

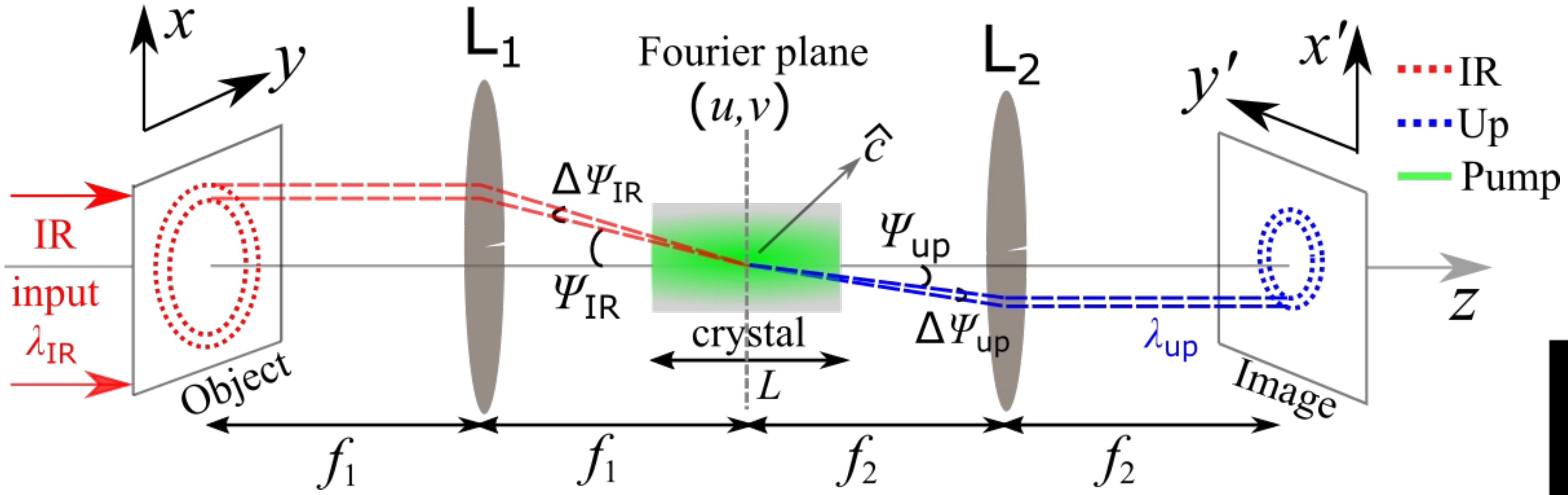




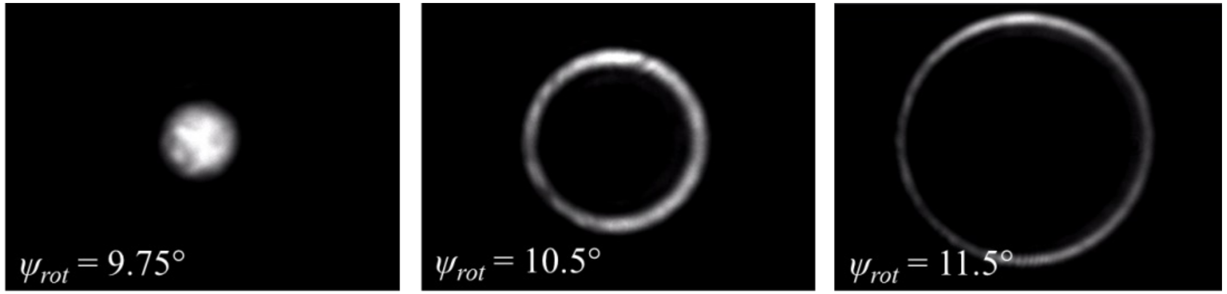


Full field of view (FoV) imaging

Monochromatic illumination



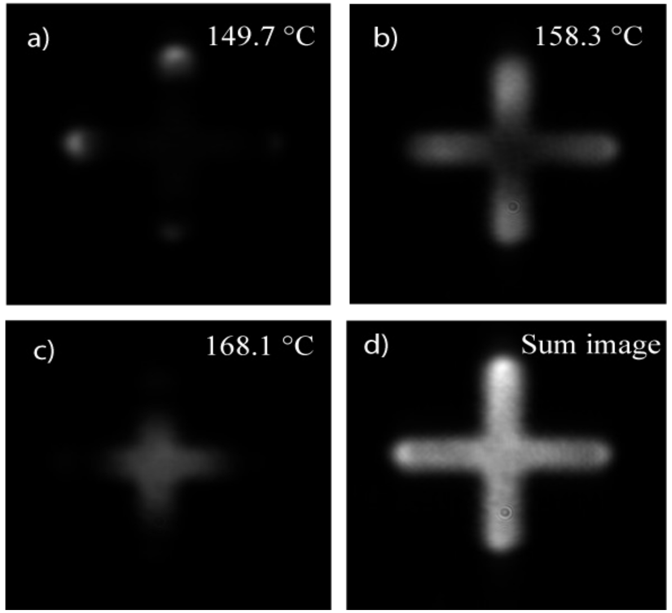
Crystal rotation, @ 6 μm, $AgGaS_2$ 10 ms for each rotation



S. Junaid, J. Tomko, M. P. Semtsiv, J. Kischkat, W. T. Masselink, C. Pedersen, and P. Tidemand-Lichtenberg, Opt. Express 26, 2203–2211 (2018)

Temperature tuning, @ 3 μm, $LiNbO_3$

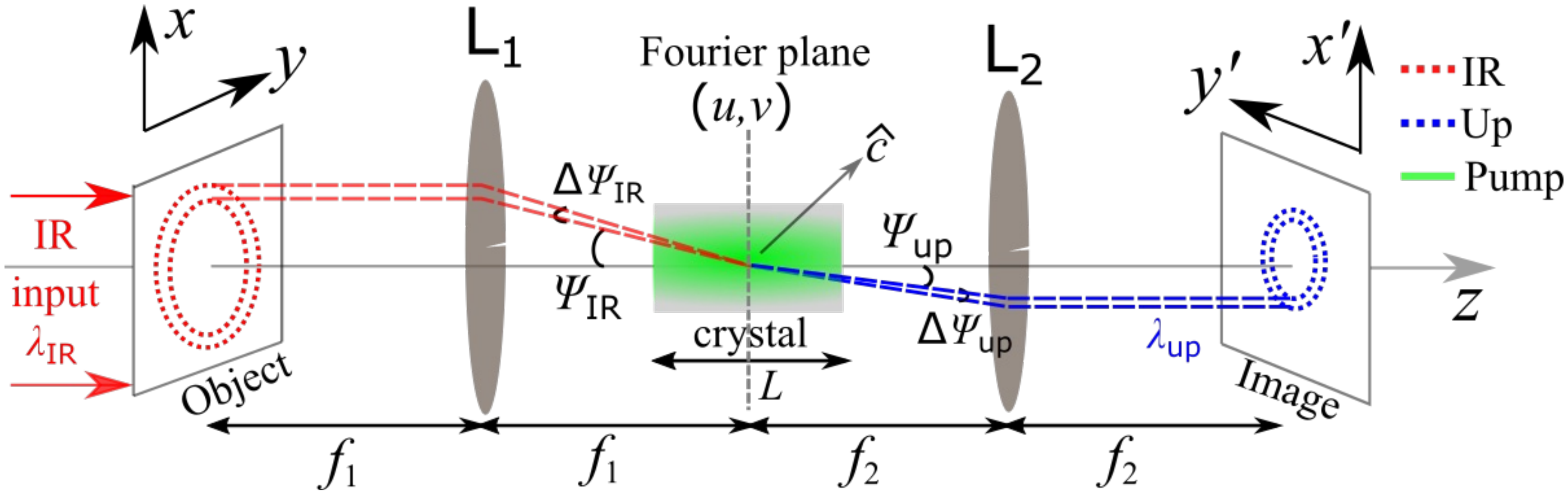
10 sec for each temp.



J. S. Dam, P. Tidemand-Lichtenberg, and C. Pedersen, Nat. Photonics 6, 788–793 (2012).

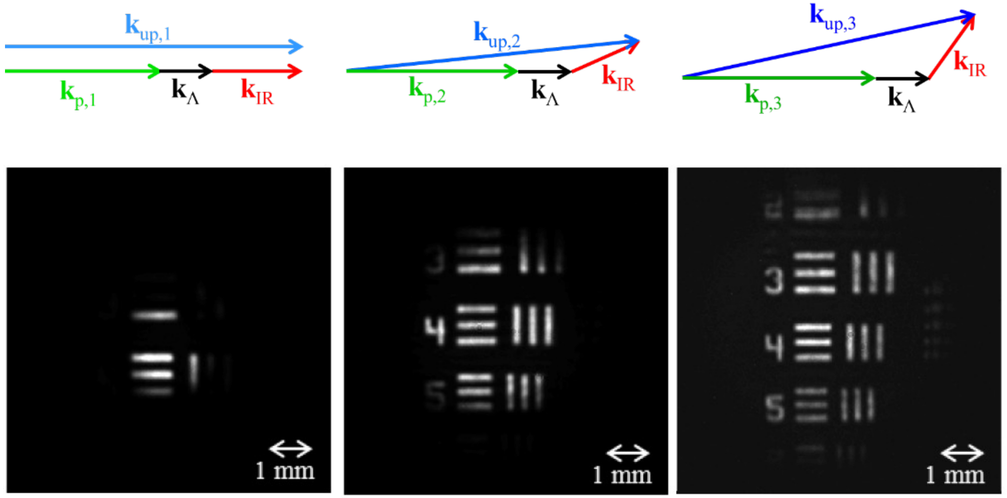
Full field of view (FoV) imaging

Monochromatic illumination

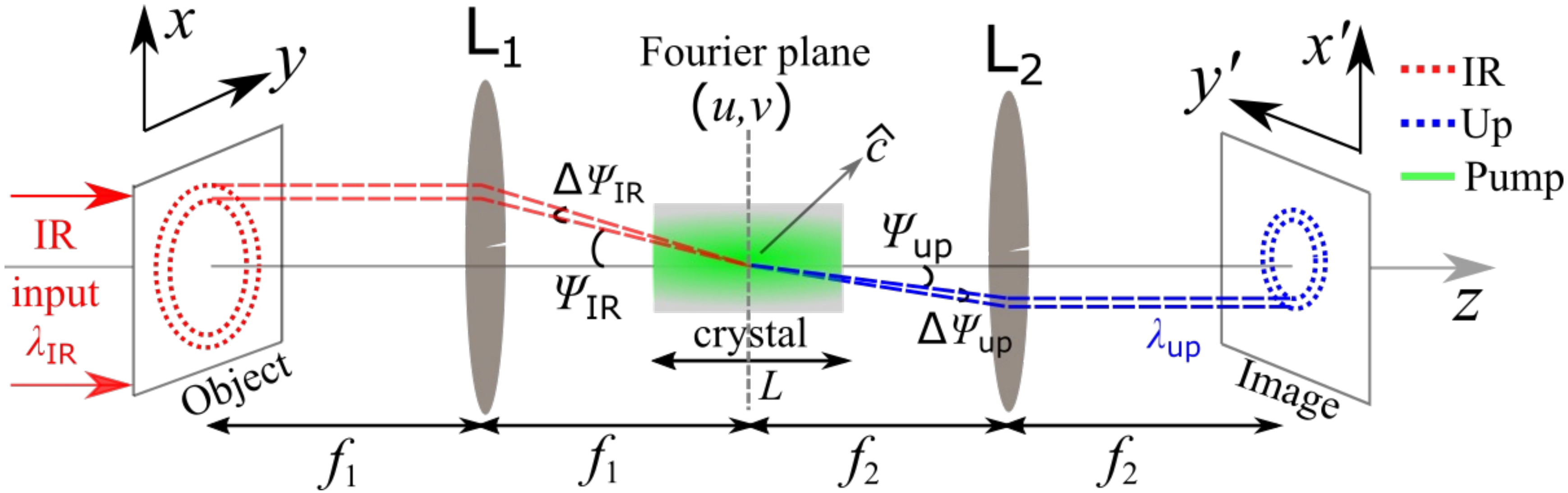


Tuning of pump wavelength
- Full FoV, @ 1550 nm
- Polychromatic up-image
- Acquisition time = 20 µs!

R. Demur, R. Garioud, A. Grisard, E. Lallier, L. Leviandier, L. Morvan, N. Treps, and C. Fabre, Opt. Express 26, 13252–13263 (2018).



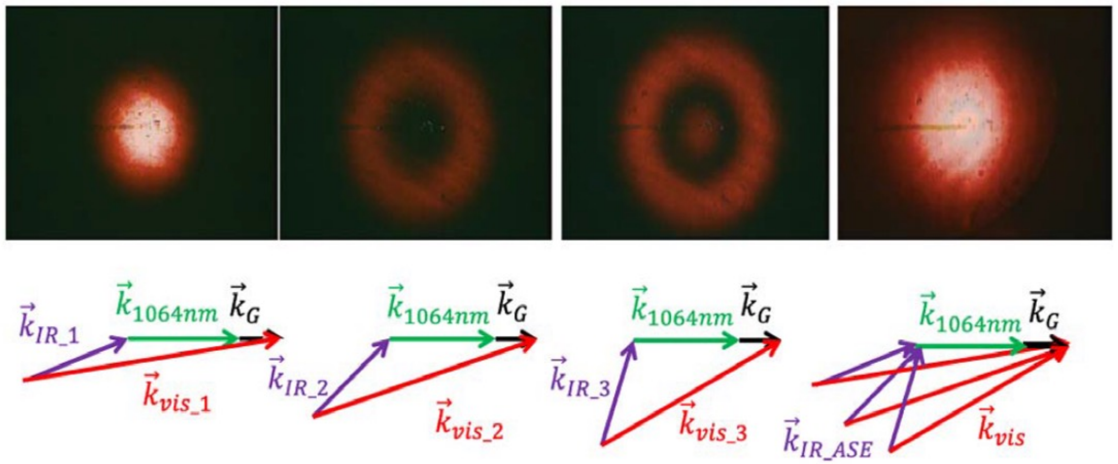
Full field of view (FoV) imaging

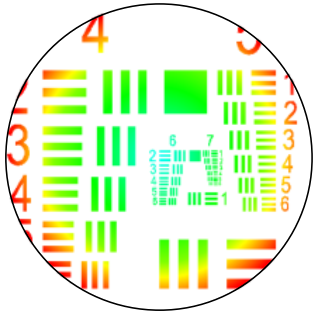


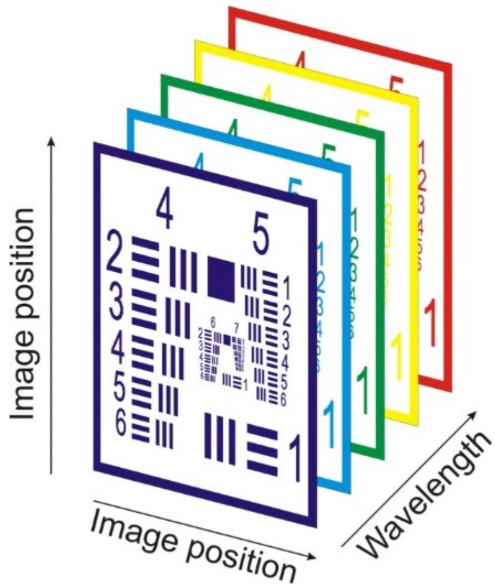
Polychromatic illumination

x – y spatial dimension
+
wavelength

Hyperspectral imaging







A. J. Torregrosa, H. Maestre, and J. Capmany, *Opt. Lett.*, vol. 40, no. 22, pp. 5315–5318 (2015)

Resolution

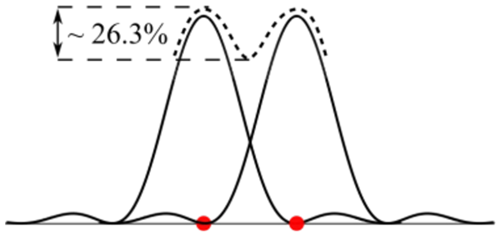
PSF: Point spread function

of resolvable elements

$$N_{\text{res}} = \frac{\left(D_{\text{up}} \cdot \text{FoV}\right)^2}{\left(D_{\text{p}} \cdot \psi_{\text{div}}\right)^2}$$

D_{up} = diameter of upconverted beam
D_p = diameter of pump beam
Ψ_{div} = far field divergence angle of the upconverted beam (sets angular res.)

Airy



PSF

Circular

Aperture

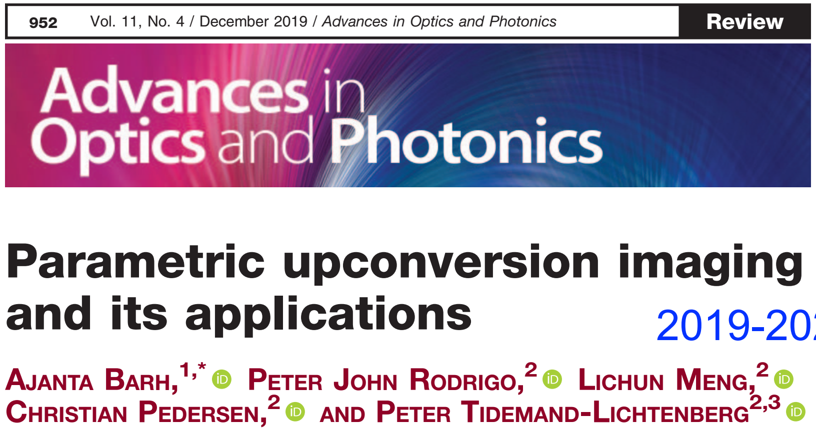
$$\frac{1.22\lambda}{D_{\text{circle}}}$$

$$\frac{\lambda}{D_{\text{width}}}$$

$$\sqrt{\ln(2)}\,\frac{4\lambda}{\pi D_{1/e}}$$

Angular Resolution

- Phase matching
- Noise
- Efficiency
- Details of imaging

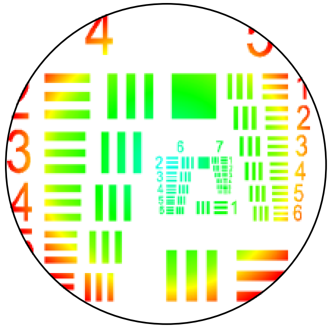

952 Vol. 11, No. 4 / December 2019 / *Advances in Optics and Photonics* **Review**

Advances in Optics and Photonics

Parametric upconversion imaging and its applications

AJANTA BARH,[1,*] PETER JOHN RODRIGO,[2] LICHUN MENG,[2] CHRISTIAN PEDERSEN,[2] AND PETER TIDEMAND-LICHTENBERG[2,3]

2019-2020



- Bluring
- Non-uniform resolution

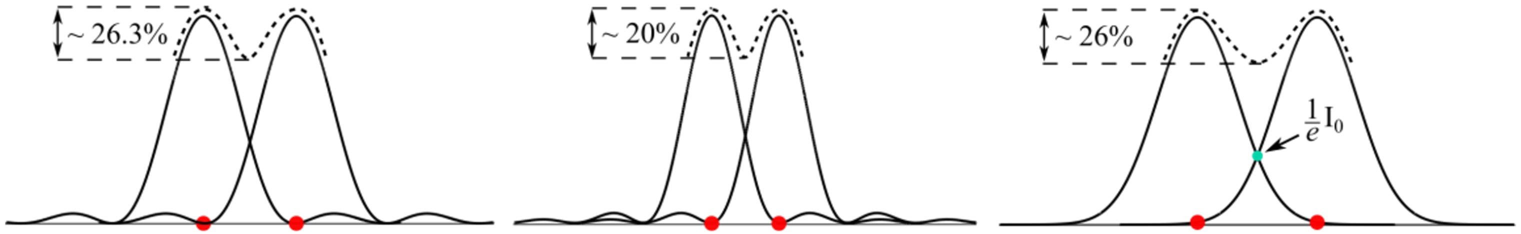
PSF: Point spread function

of resolvable elements

$$N_{\text{res}} = \frac{\left(D_{\text{up}} \cdot \text{FoV}\right)^2}{\left(D_{\text{p}} \cdot \psi_{\text{div}}\right)^2}$$

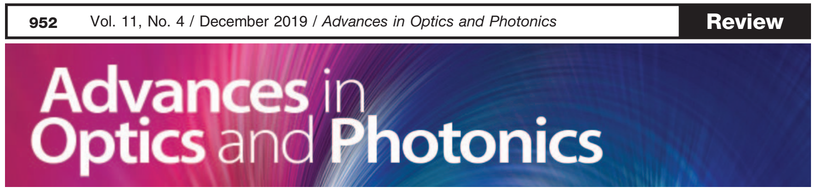
D_{up} = diameter of upconverted beam
D_{p} = diameter of pump beam
Ψ_{div} = far field divergence angle of the upconverted beam (sets angular res.)

	Airy	Sinc^2	Gaussian
PSF			



Aperture	Circular	Square	Gaussian
Angular Resolution	$\frac{1.22\lambda}{D_{\text{circle}}}$	$\frac{\lambda}{D_{\text{width}}}$	$\sqrt{\ln(2)}\frac{4\lambda}{\pi D_{1/e}}$

- Phase matching
- Noise
- Efficiency
- Details of imaging


952 Vol. 11, No. 4 / December 2019 / *Advances in Optics and Photonics* **Review**

Advances in Optics and Photonics

Parametric upconversion imaging and its applications

AJANTA BARH,[1,*] PETER JOHN RODRIGO,[2] LICHUN MENG,[2] CHRISTIAN PEDERSEN,[2] AND PETER TIDEMAND-LICHTENBERG[2,3]

2019-2020


Research Article Vol. 7, No. 7 / July 2019 / *Photonics Research* 783

PHOTONICS Research

Mid-infrared upconversion imaging using femtosecond pulses

ASHIK A. S.,[1,*] CALLUM F. O'DONNELL,[2,3] S. CHAITANYA KUMAR,[2,3] M. EBRAHIM-ZADEH,[2,3,4] P. TIDEMAND-LICHTENBERG,[1] AND C. PEDERSEN[1]

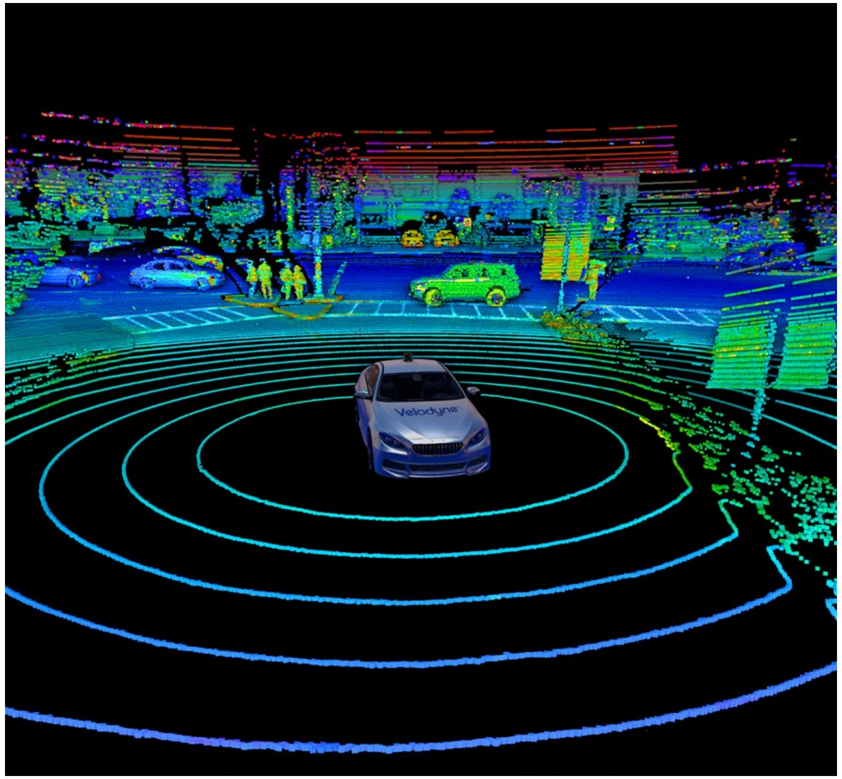
2019

Application examples and progress

LIDAR technology for autonomous vehicles

1550 nm -> low-loss, eye-safe

	InGaAs	Si-PMT
Responsivity (A/W)	1	$\sim 10^4$ (Including PMT Gain)
Dark Current (nA)	0.8	1.3

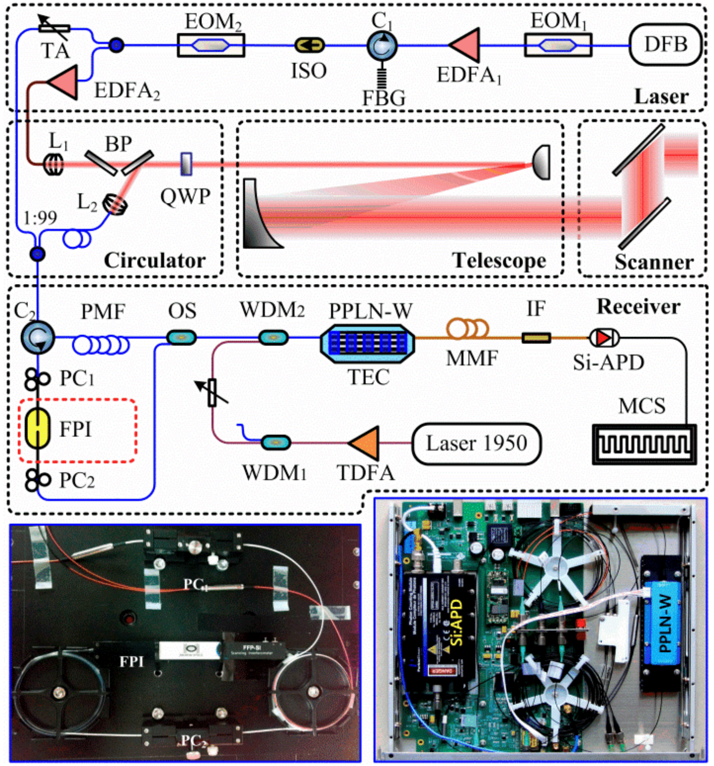


https://metrology.news/nikon-invests-in-3d-lidar/

Application example: long-distance ranging

LIDAR technology for autonomous vehicles

1550 nm -> low-loss, eye-safe

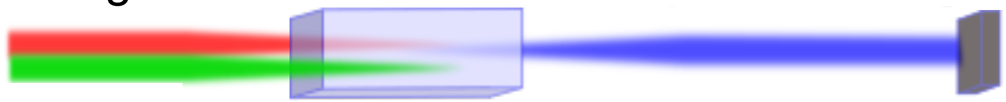


http://www.lidarx.com/aero.html
P_{pulse}=110μJ, R=15 kHz, P_{pulse}=800mW

	InGaAs	Si-PMT
Responsivity (A/W)	1	$\sim 10^4$ (Including PMT Gain)
Dark Current (nA)	0.8	1.3

Visibility LIDAR

PPLN waveguide, η_{up}**> 90%**



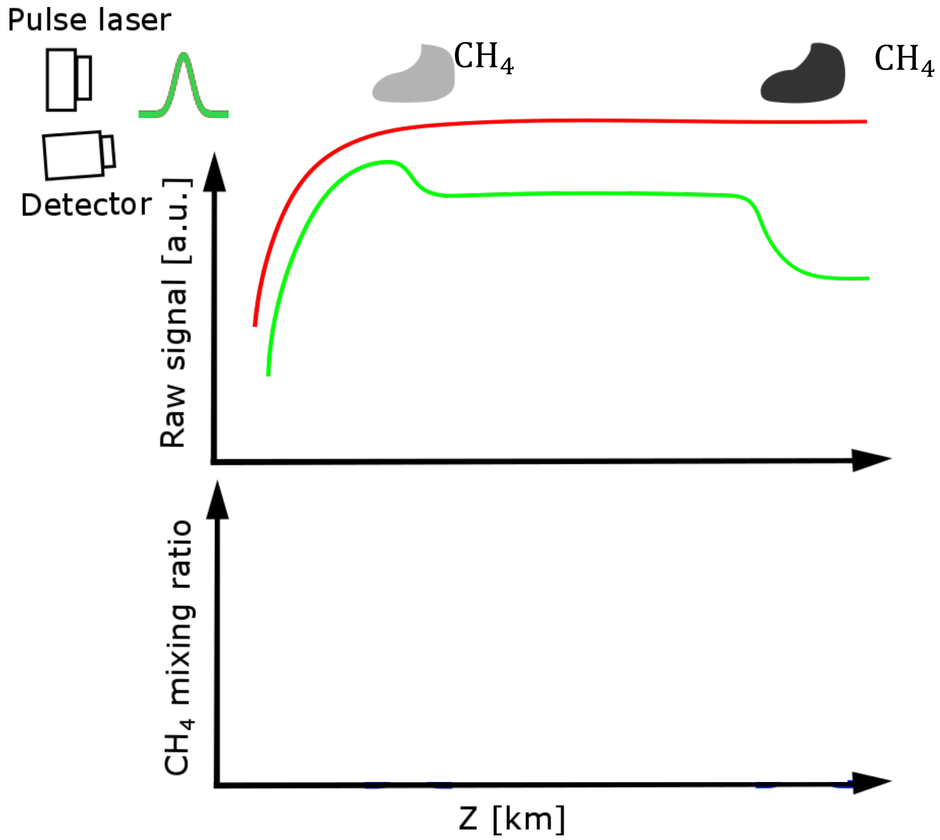
Application example: long-distance ranging

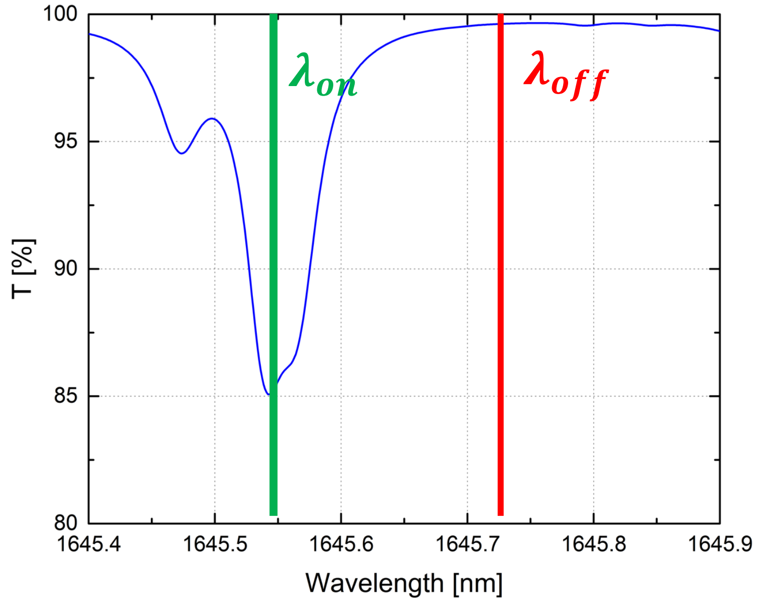
Differential Absorption Lidar (DIAL)

atmospheric gas sensing

Methane (CH_4)

	InGaAs	Si-PMT
Responsivity (A/W)	1	$\sim 10^4$ (Including PMT Gain)
Dark Current (nA)	0.8	1.3





L. Meng et al. Opt. Express **26**, 3850-3860 (2018)

Application example: MIR-OCT

World's 1st real-time MIR-OCT in the 3.5 – 5 μm range is realized using a broadband upconvertion detector

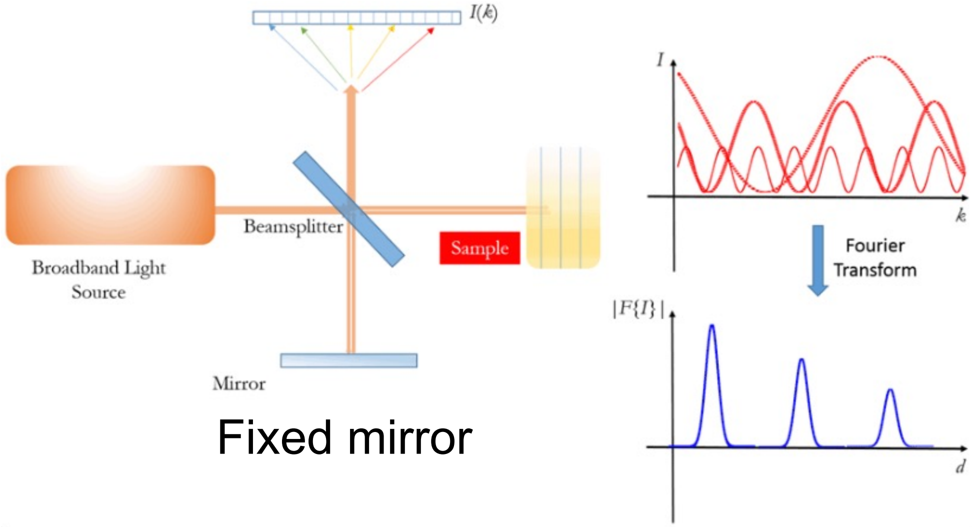
$$\delta z = \frac{2\lambda_0^2 \ln 2}{\pi . n_g \Delta\lambda}$$

Broad bandwidth, fast detection

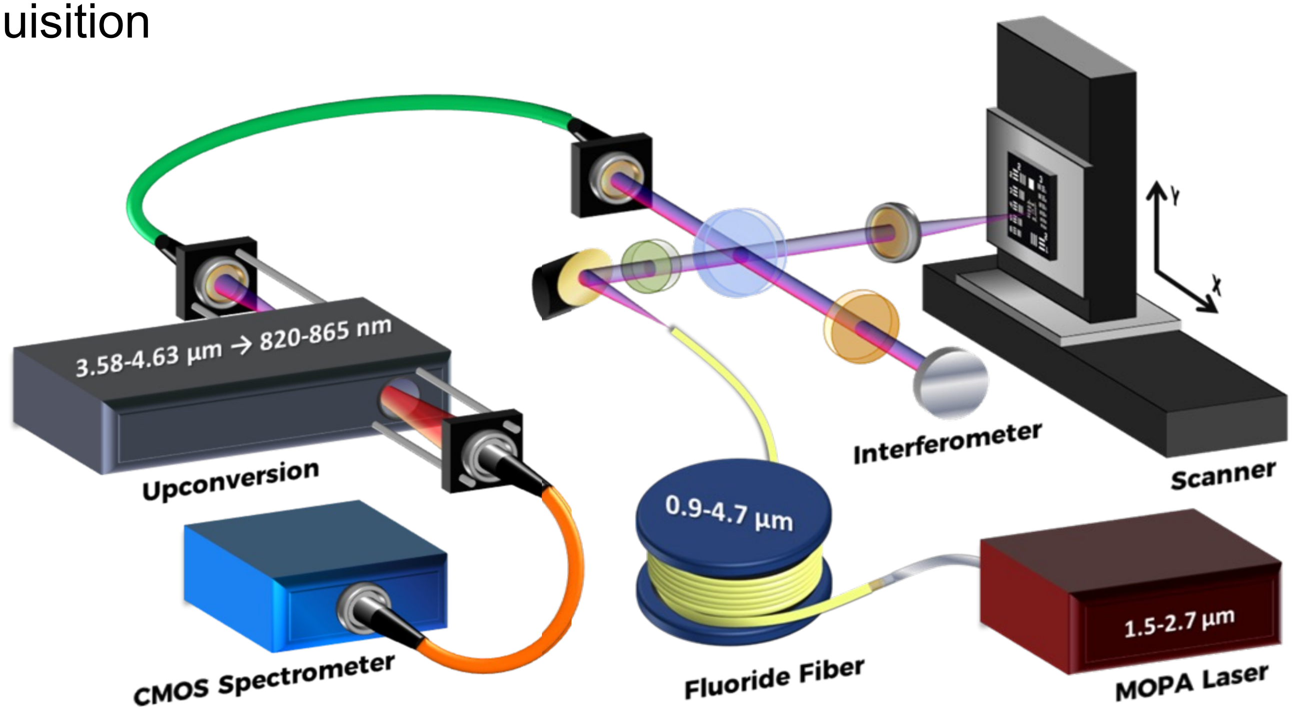
A-scan (depth) = 0.3 kHz
B-scan of 1000 lines in 3 sec

Optical coherence tomography (OCT)
- Depth imaging in highly scattering media
- High resolution (interferometric config.)
- High frame rate
- Large volumetric imaging -> high speed data acquisition

Fourier domain-OCT



Fixed mirror



Application example: MIR-OCT

Light Science & Applications
nature

ARTICLE

Real-time high-resolution mid-infrared optical coherence tomography

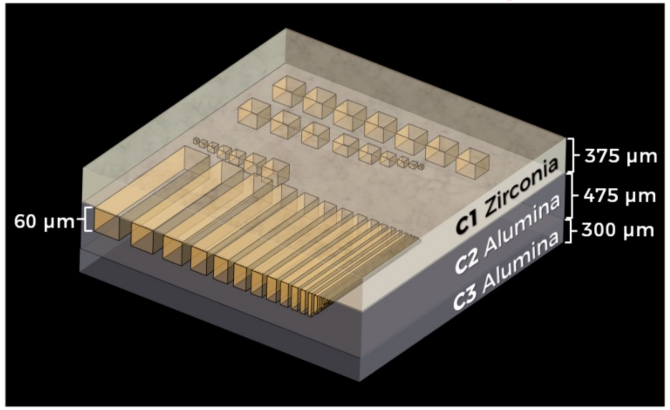
2019

Niels M. Israelsen[1,2], Christian R. Petersen[1,2], Ajanta Barh[1], Deepak Jain[1], Mikkel Jensen[1], Peter Tidemand-Lichtenberg[1,4], Christian Pedersen[1,4], Adrian Podoleanu[5] and Ole Bang[1,2]

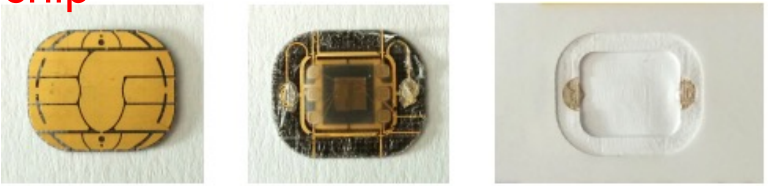
Axial resolution 8.6 µm

Structured ceramic sample

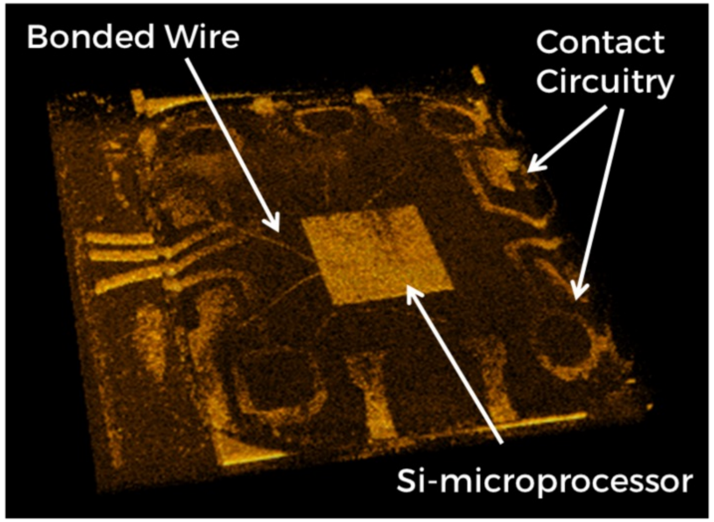
a



chip



(a) front of module (b) back of module (c) hole in card body



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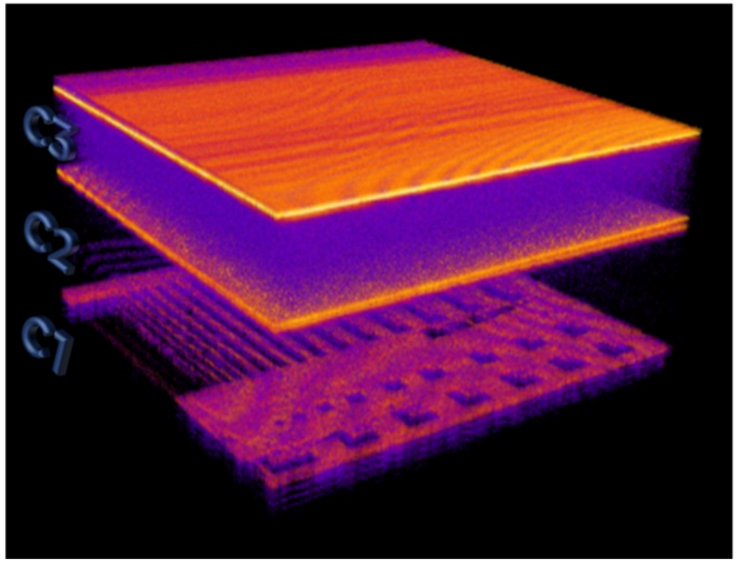
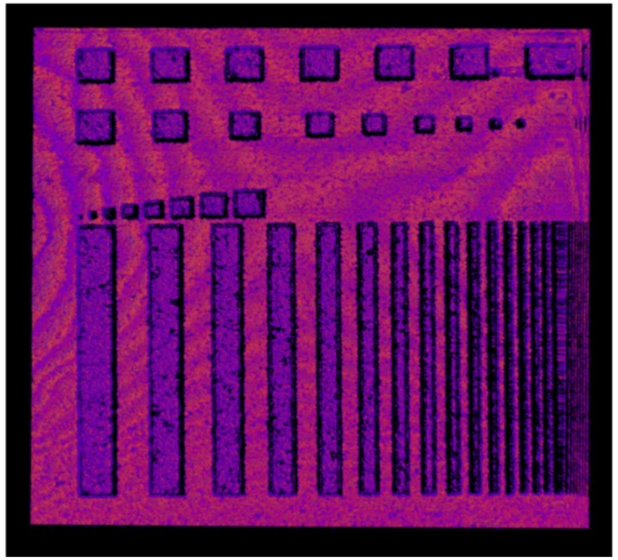
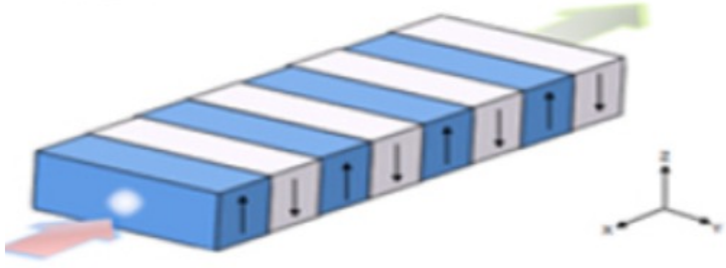


g

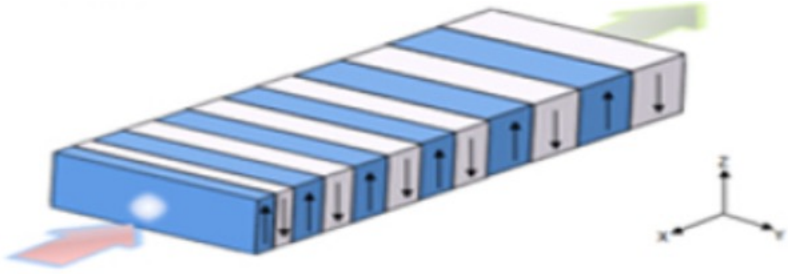


Current status of MIR-OCT

1st version:
- PPLN with fixed period
- Non-collinear phase-matching



2nd version:
- PPLN with chirped period
- Near-collinear phase-matching



4558 Vol. 46, No. 18 / 15 September 2021 / *Optics Letters* **Letter**

Optics Letters

High-resolution mid-infrared optical coherence tomography with kHz line rate 2021

NIELS M. ISRAELSEN,[1,2,*] PETER JOHN RODRIGO,[1] CHRISTIAN R. PETERSEN,[1,2] GETINET WOYESSA,[1] RASMUS E. HANSEN,[1] PETER TIDEMAND-LICHTENBERG,[1,3] CHRISTIAN PEDERSEN,[1,3] AND OLE BANG[1,2,4]

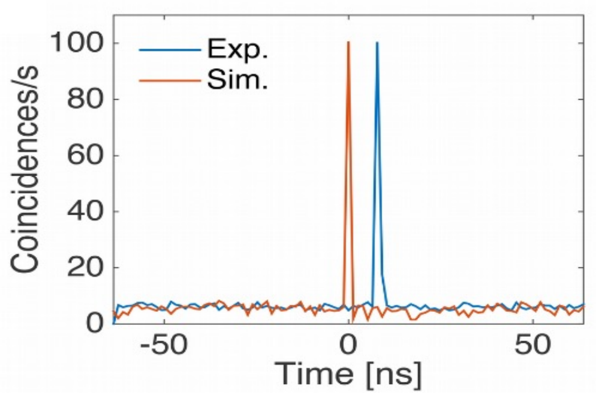
	1st version	2nd version
A-scan rate	0.3 kHz	3 kHz
Axial resolution	8.6 µm	5.8 µm

Spin-off NORBLIS (2018) – prototypes are under development
- Ceramic structure
- Paint/coating layers

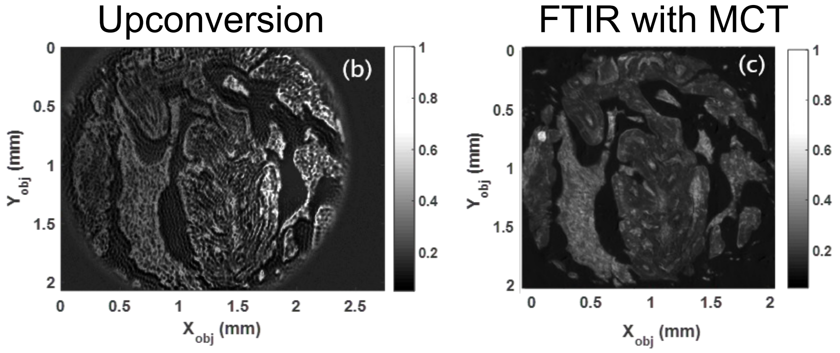
What else?

- Quantum: Single-photon coincidence measurement

  Nature Comm. 8, 15184 (2017)

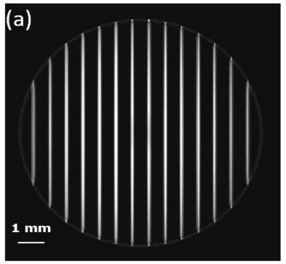


- Hyperspectral imaging: bio-tissue, cancer diagnostics



- PSF engineering: Phase contrast imaging

  Appl. Opt. 59, 2157-2164 (2020)



Thank you!